THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Digitalization as Facilitator of Effective Information Sharing in Production Systems

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Cover:
Shop-floor operators (from Figure 1.1) occupies the centre stage of the cover illustration. The icons to the left and right represent information-sharing capabilities before and after a digital transformation.

The icons were originally designed by Freepik, Eucalyp, and xnimrod from Flaticon.

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ABSTRACT

This thesis aims to formulate strategic approaches to digital transformation, which manufacturing companies can apply to make themselves more effective in disseminating and presenting production-related information to shop-floor operators. Therefore, two approaches are proposed. One focuses on disseminating information in production systems; the other focuses on presenting information to shop-floor operators.

First, assessing digital maturity can facilitate the effective dissemination of information in production systems and contribute towards a digital transformation to Industry 4.0. Maturity assessments provide an understanding of current capabilities. This enables the formulation of goals for digital transformations and, subsequently, facilitates the creation of development plans to make disseminating information more effective.

Second, applying digital technologies can facilitate new capabilities for presenting information to operators and contribute towards a digital transformation to Operator 4.0. Operators work under varying circumstances, which requires varying types of information as cognitive support. Understanding these situational requirements facilitates the selection and subsequent implementation of suitable digital technologies for presenting information to operators more effectively.

Together, these two approaches demonstrate how digitalization can facilitate effective information sharing in production systems and for shop-floor operators.

Keywords: digital transformation, digital maturity, data, information, knowledge, dissemination, assessment, manufacturing, Industry 4.0, Operator 4.0

ACKNOWLEDGEMENTS

At last, I am reassured and optimistic as this leg of my quest for knowledge draws nearer to its finale. For the past five years, my mind, work and life have been devoted to the research efforts and scientific inquiry condensed in this thesis. Here, I leave a slice of my insights and deductions for the benefit of others to scrutinize and use. Throughout this winding journey, I have grown and developed both personally and professionally. Hopefully; I have become a better researcher and philosopher.

Beyond any individual effort lie the collaborations that all academic research depends on, mine included. My accomplishments would not have been possible without the many people I have become acquainted with during this journey. I have benefitted greatly from their shared information and knowledge, help and support, guidance and direction, plus their encouraging words.

Consequently, I would first and foremost like to express my deepest gratitude to my supervisors, to whom I owe my accomplishments. *Åsa Fast-Berglund*, you have given me many opportunities and responsibilities, and have trusted me to succeed. Thanks to you, I have developed as a doer. *Dan Paulin*, you have given me invaluable advice and space for reflection. Thanks to you, I have developed as a thinker. Both of you have challenged me and my thinking but also provided me with tools along my doctoral journey. I hope that guiding me has also been rewarding for you. Thank you both for your counsel, patience, and belief in me.

Delight is my main emotion as I thank *Johan Stahre* for welcoming me under his aegis at our *Division of Production Systems* and *Department of Industrial and Materials Science*. Your counsel always gave me a fresh perspective on my research. Thank you for creating the setting, conditions, and structures that have enabled and facilitated my research and everyday working life. This has been a great workplace with a friendly atmosphere and I have enjoyed working and interacting with the people here. I would also like to thank all my colleagues, past and present, both academics and administrative staff, as well as all my students, for contributing to this positive sense of progress and accomplishment.

Essential to my research activities are the research projects of which I have been a part. Four of them were funded by *Vinnova*, the *Swedish Governmental Agency for Innovation Systems* through the programmes *Fordonsstrategisk forskning och innovation (FFI)* and *Produktion2030*. One project was funded by the *Swedish National Space Agency* through its programme *Nationellt rymdtekniskt forskningsprogram (NRFP)*. This important contribution is gratefully acknowledged. Within these research projects, I have had the pleasure to work alongside many people and manufacturing companies, all of whom have been important to my research. Thank you for a wonderful collaboration. In this context, I am also thankful for two things. First, the project leadership entrusted to me in the FFI project *Instruction Innovation for Cognitive Optimisation (TACO)*. Second, the many network-building opportunities through Produktion2030, which will be fondly remembered in these times of travel restrictions.

From the onset of my doctoral journey, I had role models close by who I could emulate. I am very thankful to *Sandra Mattsson*, *Magnus Åkerman*, and *Pierre Johansson* for sharing their experiences, opening up paths, and giving me inspiration. I hope I have been as supportive and inspiring to subsequent PhD candidates as you were to me.

Going to *Stena Industry Innovation Laboratory* for research, education, and utilization activities was made all the more enjoyable thanks to my close allies, *Omkar Salunkhe*, *Malin Tarrar*, *Peter Thorvald*, and *Sven Ekered*. Thank you for our serious scientific discussions and many moments of laughter.

Humble beginnings have produced some mature researchers. From our first stumbling undergraduate steps, we now approach this doctoral milestone. *Daniel Nåfors* and *Anna Landström*, I cherish your friendship and camaraderie through these similar journeys of ours.

I am very grateful and happy to be part of my dear family. To my mother *Liya Sang*, father *Martin Li*, and my brother *Sten Li*, thank you for allowing me to enjoy your unconditional love and support in my endeavours.

Journeying forward, I humbly reflect upon the serendipitous circumstances of my upbringing. This small corner of the world I call home enjoys a level of prosperity not open to all. I recognize that peace, free education, good healthcare, freedom of movement, access to information, and many other privileges have given me time and space to ponder the intricacies of the world. While my scientific contribution may be minor, I sincerely hope I have made everyday life a little bit better for some.

Dan Li
Gothenburg, September 2021

LIST OF APPENDED PAPERS

The five appended papers in this thesis are listed here, along with the contributions and distribution of work among the authors.

Paper I **Human-Centred Dissemination of Data, Information and Knowledge in Industry 4.0**

Dan Li, Anna Landström, Åsa Fast-Berglund, and Peter Almström (2019a)

Presented at the *29th CIRP Design Conference*, Póvoa de Varzim, 8-10 May. Published in *Procedia CIRP*, vol. 84, pp. 380-386.

Dan Li initiated and wrote the paper together with Anna Landström with contributions from Åsa Fast-Berglund and Peter Almström. Dan Li and Anna Landström planned the study, collected, and analysed the literature.

Paper II **Current and Future Industry 4.0 Capabilities for Information and Knowledge Sharing**

Dan Li, Åsa Fast-Berglund, and Dan Paulin (2019b)

Published in *the International Journal of Advanced Manufacturing Technology*, vol. 105, pp. 3951-3963.

Dan Li initiated and wrote the paper with contributions from Åsa Fast-Berglund and Dan Paulin. Dan Li, Åsa Fast-Berglund, and Dan Paulin planned the study. Dan Li collected and analysed the empirical data.

Paper III **Forming a Cognitive Automation Strategy for Operator 4.0 in Complex Assembly**

Sandra Mattsson, Åsa Fast-Berglund, **Dan Li**, and Peter Thorvald (2020)

Published in *Computers & Industrial Engineering*, vol. 139, article 105360.

Sandra Mattsson and Åsa Fast-Berglund initiated the paper. Sandra Mattsson wrote the paper with contributions from Åsa Fast-Berglund and Dan Li. Sandra Mattsson conceptualized the model with contributions from Åsa Fast-Berglund, Dan Li, and Peter Thorvald.

Paper IV **Industry 4.0 Maturity and its Implications for Information Sharing on Shop Floors**

Dan Li, Malin Tarrar, Magnus Åkerman, Åsa Fast-Berglund, and Dan Paulin

Manuscript in preparation. Submitted to a scientific journal.

Dan Li initiated and wrote the paper with contributions from Malin Tarrar, Magnus Åkerman, Åsa Fast-Berglund, and Dan Paulin. Dan Li planned the study. Dan Li, Malin Tarrar, and Magnus Åkerman collected and analysed the empirical data. Dan Li and Magnus Åkerman conceptualized the model with contributions from Malin Tarrar.

Paper V **Exploration of Digitalized Presentation of Information for Operator 4.0**

Dan Li, Åsa Fast-Berglund, Dan Paulin, and Peter Thorvald

Manuscript in preparation. In the review process of a scientific journal.

Dan Li initiated and wrote the paper with contributions from Åsa Fast-Berglund, Dan Paulin, and Peter Thorvald. Dan Li and Åsa Fast-Berglund planned the study. Dan Li and Åsa Fast-Berglund conceptualized the theoretical framework with contributions from Dan Paulin and Peter Thorvald. Dan Li collected and analysed the empirical data.

LIST OF ADDITIONAL PAPERS

This list of additional papers includes related work, important for the content of this thesis but outside of the scope for answering the research questions.

Paper 1 **How Changes in Cognitive Automation Can Affect Operator Performance and Productivity**

Dan Li, Anna Landström, Sandra Mattsson, and Malin Karlsson (2014)

Presented at the *6th Swedish Production Symposium*, Gothenburg, 16-18 September.

Paper 2 **Testing Operator Support Tools for a Global Production Strategy**

Dan Li, Sandra Mattsson, Åsa Fast-Berglund, and Magnus Åkerman (2016a)

Presented at the *6th CIRP Conference on Assembly Technologies and Systems*, Gothenburg, 16-18 May.
Published in *Procedia CIRP*, vol. 44, pp. 120-125.

Paper 3 **Evaluation of Guidelines for Assembly Instructions**

Sandra Mattsson, Åsa Fast-Berglund, and **Dan Li** (2016)

Presented at the *8th IFAC Conference on Manufacturing Modelling, Management and Control*, Troyes, 28-30 June.
Published in *IFAC-PapersOnLine*, vol. 49, no. 12, pp. 209-214.

Paper 4 **Towards an Assessment Approach Promoting Flexible Value-Adding Meetings in Industry**

Ulrika Harlin, Åsa Fast-Berglund, **Dan Li**, and Leif Funke (2016)

Presented at the *7th Swedish Production Symposium*, Lund, 25-26 October.

Paper 5 **Identifying Improvement Areas in Production Planning Meetings by Assessing Organisation and Information Systems at a Small Production Company**

Dan Li, Åsa Fast-Berglund, Per Gullander, and Lars Ruud (2016b)

Presented at the *7th Swedish Production Symposium*, Lund, 25-26 October.

Paper 6 **Measuring Operator Emotion Objectively at a Complex Final Assembly Station**

Sandra Mattsson, **Dan Li**, Åsa Fast-Berglund, and Liang Gong (2017)

Presented at the *7th International Conference on Applied Human Factors and Ergonomics*, Orlando, Florida, 27-31 July (2016).
Published in Hale, K. and Stanney, K. (eds.) *Advances in Neuroergonomics and Cognitive Engineering*, part of series Advances in Intelligent Systems and Computing, vol. 488, pp. 223-232, Springer, Cham.

Paper 7 **The Comparison Study of Different Operator Support Tools for Assembly Task in the Era of Global Production**

Liang Gong, **Dan Li**, Sandra Mattsson, Magnus Åkerman, and Åsa Fast-Berglund (2017)

Presented at the *27th International Conference on Flexible Automation and Intelligent Manufacturing*, Modena, 27-30 June.
Published in *Procedia Manufacturing*, vol. 11, pp. 1271-1278.

Paper 8 **Digitalization of Whiteboard for Work Task Allocation to Support Information Sharing between Operators and Supervisor**

Dan Li, Åsa Fast-Berglund, Anna Dean, and Lars Ruud (2017)

Presented at the *20th World Congress of the International Federation of Automatic Control*, Toulouse, 9-14 July.
Published in *IFAC PapersOnLine*, vol. 50, no. 1, pp. 13044-13051.

Paper 9 **Application of Design Principles for Assembly Instructions – Evaluation of Practitioner Use**

Sandra Mattsson, **Dan Li**, and Åsa Fast-Berglund (2018a)

Presented at the *7th CIRP Conference on Assembly Technologies and Systems*, Tianjin, 10-12 May.
Published in *Procedia CIRP*, vol. 76, pp. 42-47.

Paper 10 **Testing and Validating Extended Reality (xR) Technologies in Manufacturing**

Åsa Fast-Berglund, Liang Gong, and **Dan Li** (2018a)

Presented at the *8th Swedish Production Symposium*, Stockholm, 16-18 May.
Published in *Procedia Manufacturing*, vol. 25, pp. 31-38.

Paper 11 **Design Concept towards a Human-Centered Learning Factory**

Sandra Mattsson, Omkar Salunke, Åsa Fast-Berglund, **Dan Li**, and Anders Skoogh (2018b)

Presented at the *8th Swedish Production Symposium*, Stockholm, 16-18 May. Published in *Procedia Manufacturing*, vol. 25, pp. 526-534.

Paper 12 **Effects of Information Content in Work Instructions for Operator Performance**

Dan Li, Sandra Mattsson, Omkar Salunkhe, Åsa Fast-Berglund, Anders Skoogh, and Jesper Broberg (2018a)

Presented at the *8th Swedish Production Symposium*, Stockholm, 16-18 May. Published in *Procedia Manufacturing*, vol. 25, pp. 628-635.

Paper 13 **Creating Strategies to Improve the Use of IT- and IS-Systems in Final Assembly**

Åsa Fast-Berglund, **Dan Li**, and Magnus Åkerman (2018b)

Presented at the *16th International Conference on Manufacturing Research*, Skövde, 11-13 September.
Published in Thorvald, P. and Case, K. (eds.) *Advances in Manufacturing Technology XXXII*, part of series Advances in Transdisciplinary Engineering, vol. 8, pp. 177-182, IOS Press, Amsterdam.

Paper 14 **Supporting Individual Needs for Intra-Organisational Knowledge Sharing Activities in Pre-Industry 4.0 SMEs**

Dan Li, Dan Paulin, Åsa Fast-Berglund, Per Gullander, and Lars-Ola Bligård (2018b)

Presented at the *15th International Conference on Intellectual Capital, Knowledge Management & Organsational Learning*, Cape Town, 29-30 November.
Published in Pather, S. (eds.) *Proceedings of the 15th International Conference on Intellectual Capital, Knowledge Management & Organsational Learning*, pp. 160-170.

Paper 15 **Conceptualising Assembly 4.0 through the Drone Factory**

Åsa Fast-Berglund, Magnus Åkerman, **Dan Li**, and Omkar Salunkhe (2019)

Presented at the *9th IFAC Conference on Manufacturing Modelling, Management and Control*, Berlin, 28-30 August.
Published in *IFAC-PapersOnLine*, vol. 52, no. 13, pp. 1525-1530.

Paper 16 **Knowledge Strategies for Organization 4.0 – A Workforce Centric Approach**

Magnus B. Gerdin, Åsa Fast-Berglund, **Dan Li**, and Adam Palmquist (2020)

Presented at the *IFIP WG 5.7 International Conference, Advances in Production Management Systems*, Novi Sad (virtually), 30 August-2 September.
Published in Lalic, B.; Majstorovic, V.; Marjanovic, U.; von Cieminski, G.; and Romero, D. (eds.) *Advances in Production Management Systems. Towards Smart and Digital Manufacturing*, part of series IFIP Advances in Information and Communication Technology, vol. 592, pp. 31-36, Springer, Cham.

Paper 17 **Concepts for Digitalisation of Assembly Instructions for Short Takt Times**

Anna Palmqvist, Emelie Vikingsson, **Dan Li**, Åsa Fast-Berglund, Niklas Lund (2020)

Presented at the *8th CIRP Conference on Assembly Technology and Systems*, Athens (virtually), 29 September-1 October.
Published in *Procedia CIRP*, vol. 97, pp. 154-159.

Paper 18 **Production Innovation and Effective Dissemination of Information for Operator 4.0**

Dan Li, Åsa Fast-Berglund, and Dan Paulin (2020)

Presented at the *9th Swedish Production Symposium*, Jönköping (virtually), 7-8 October.
Published in Säfsten, K. and Elgh, F. (eds.) *SPS2020: Proceedings of the Swedish Production Symposium*, part of series Advances in Transdisciplinary Engineering, vol. 13, pp. 229-238, IOS Press, Amsterdam.

In general, the additional papers have contributed with knowledge about information sharing in production systems and on shop floors, both in a learning factory environment and from industrial cases. Together, Papers 1-17 created the rationale for Paper I. Paper 18, which was published after Paper I, provides additional commentary and discusses the topic from an innovation perspective.

Papers 4, 5, 8, 13, 14, and 16 contributes with knowledge about digitalization technologies, meetings, and informational needs of operators and other stakeholders in production systems. This has created the foundation for the research work mainly conducted in Papers II and IV.

Papers 1, 2, 3, 6, 7, 9, 10, 11, 12, 15, and 17 contributes with knowledge about assembly instructions and how shop-floor operators use them. This has created the foundation for the research work mainly conducted in Papers III and V.

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1

INTRODUCTION

This chapter introduces the research area of production systems, emphasising information sharing and digital technologies and further arguing for the importance of disseminating information in production systems and presenting it to operators. This leads to the aims and research questions presented in this thesis.

1.1 BACKGROUND

In recent decades, the manufacturing industry has shifted its focus from mass production to mass customization and, further, towards personalized production (Jovane et al., 2003; Hu et al., 2011; ElMaraghy et al., 2013). While mass production on dedicated manufacturing lines is cost-efficient for high volume products, flexible and reconfigurable manufacturing systems allow mass customization, with product variety and customization delivering products that cater for customer needs and options (Jovane et al., 2003; ElMaraghy, 2006; Koren and Shpitalni, 2010). This paradigm shift is pushing many manufacturing companies to transform their production systems towards personalized production as a strategy to gain competitive advantage (Jovane et al., 2003; Hu et al., 2011; Dalenogare et al., 2018; ElMaraghy et al., 2021).

However, this opportunity requires manufacturing companies to become capable of managing more production-related data, information, and knowledge in their production systems (Inkinen, 2016; DalleMule and Davenport, 2017). The rapid development of digital technologies is providing opportunities for manufacturing companies to manage the increase in production-related data, information, and knowledge as their production systems undergo digital transformations (Oesterreich and Teuteberg, 2016; Cohen et al., 2019). Industry 4.0 and its associated enabling technologies is driving the manufacturing industry's paradigm shift (Lasi et al., 2014; Yao and Lin, 2016; Liao et al., 2017; Chari et al., 2021). Nevertheless, the emergence of new digital technologies does not translate directly to their direct implementation (van Lente et al., 2013) and effort needs to be put into promoting its use on shop floors (Dedehayir and Steinert, 2016).

The manufacturing industry is changing and so is the future of industrial work for shop-floor operators. Their work tasks will require problem-solving capabilities and knowledge-based reasoning, as predicted and now evidenced (Autor, 2015; Bortolini et al., 2017; Waschull et al., 2020; Aranda Muñoz et al., 2021; ElMaraghy et al., 2021). In the Industry 4.0 context in which Operator 4.0 works, digital technologies can provide cognitive support, create socially sustainable work environments, and enable Operator 4.0 to work effectively (Kadir et al., 2019; Romero et al., 2020). However, the implementation of digital technologies will affect both process and organizational innovations (Li et al., 2020).

On a global level, increased digitalization and the implementation of Industry 4.0-related technologies can support manufacturing companies in managing shop-floor-related information but brings challenges of its own (Johansson et al., 2019). On shop floors, Industry 4.0 can facilitate human cooperation because it supports the way data, information, and knowledge are disseminated (Li et al., 2018b). This dissemination occurs in three dimensions: (1) horizontal through the value chain, (2) engineering end-to-end for production realization, and (3) vertical (Kagermann et al., 2013; Liao et al., 2017; Pereira and Romero, 2017; Alcácer and Cruz-Machado, 2019).

Although they are digitalized, manufacturing companies rarely have integrated IT systems for disseminating information in their production systems. This could enable near real-time aggregation and visualization of information and reduce manual handling when transferring it (Schuh et al., 2020b). For many shop-floor operators, presenting previously digitized information is a paper-based activity (Johansson et al., 2019; Palmqvist et al., 2020). This creates challenges for operators because assembly work is supported (or hindered) by poor quality or overly generic instructions regarding the task at hand (Johansson et al., 2019).

Maturity models serve as useful guidance tools for manufacturing companies during their digital transformations. They help in assessing the current situation and developing roadmaps (Schumacher et al., 2016; Machado et al., 2019). They should never be seen as an easy route to attaining Industry 4.0. However, they may support a digital transformation by facilitating reflection on a company's current Industry 4.0 capabilities and allowing subsequent formulation of strategies and action plans (Schumacher et al., 2016; Colli et al., 2019).

Increasing cognitive automation changes the way work is done; it shifts operators from manual labour towards more knowledge-based work (Gleeson et al., 2019; Berlin and Söderström, 2020; ElMaraghy et al., 2021). Furthermore, cognitive automation bolsters human cognition in complex production systems and may improve productivity when complexity is properly managed (Lindblom and Thorvald, 2017; Jiao et al., 2020). Applying a human-centred approach to production development by involving operators has many positive effects on continuous improvement efforts (Longoni and Cagliano, 2014; Lam et al., 2015). This is particularly so, if valuable knowledge and experience can be elicited and disseminated (Tamayo-Torres et al., 2014; Brennan et al., 2015). One aspect for companies to consider when implementing support systems for operators is the operators' individual needs and information preferences (Haghi et al., 2018). The information may then be visualized in an appealing or palatable manner (Thoben et al., 2017; Landström et al., 2018). This, in turn, demands that an organization should involve its operators in the design process (Bauer et al., 2017).

Even though many new technologies are being developed and off-the-shelf solutions are available, it is still difficult to implement technologies that support operators (Stentoft et al., 2019). Often, this is because the automation solution has not been implemented in a way that people find useful (Parasuraman and Riley 1997). Successfully implementing digital technologies in production systems requires a holistic approach; one which considers both technological opportunities and organizational foundations (Schumacher et al., 2016; Schuh et al., 2020a).

This narrows the main research interest down to production system shop floors, where information is shared. While increased competitiveness drives the sharing of more information, new digital technologies could enable companies to share new types of information in new ways. However, implementing this on the shop floor requires a human-centred perspective. This intersection of ideas leads into the purpose and aim of this thesis.

1.2 AIM AND RESEARCH QUESTIONS

The purpose of this research is to enable manufacturing companies to share production-related information more effectively within their production systems. This cause may potentially be furthered by technological development through increased digitalization. The general capability of effectively sharing information helps companies to manage complexity, for their production systems and shop-floor operators.

Hence, the aim of this thesis is to formulate strategic approaches to digital transformation which manufacturing companies can apply. This will make them more effective in disseminating and presenting production-related information to shop-floor operators.

Sharing information digitally or, more specifically, disseminating and presenting information, requires different approaches if it is to be effective. This highlights the necessity of disseminating information and the quality of that information content.

Two research questions have been formulated in support of this aim.

RQ1: How can assessing digital maturity facilitate the effective dissemination of information in production systems?

In terms of disseminating information, using digital technologies allows this to be done more effectively and expediently in production systems. Thus, digital technologies can support manufacturing companies in collecting, analysing, and spreading production-related information in production systems.

Maturity models may be applied in this context, to help understand companies' current levels of digitalization and capability to disseminate information. By conducting analyses on current maturity levels, companies' current and possible future capabilities may be understood, thus contributing to prospective digital transformations.

Hence, RQ1 focuses on exploring digital transformations from a production systems perspective, with the emphasis on maturing towards Industry 4.0.

RQ2: How can applying digital technologies facilitate the effective presentation of information to shop-floor operators?

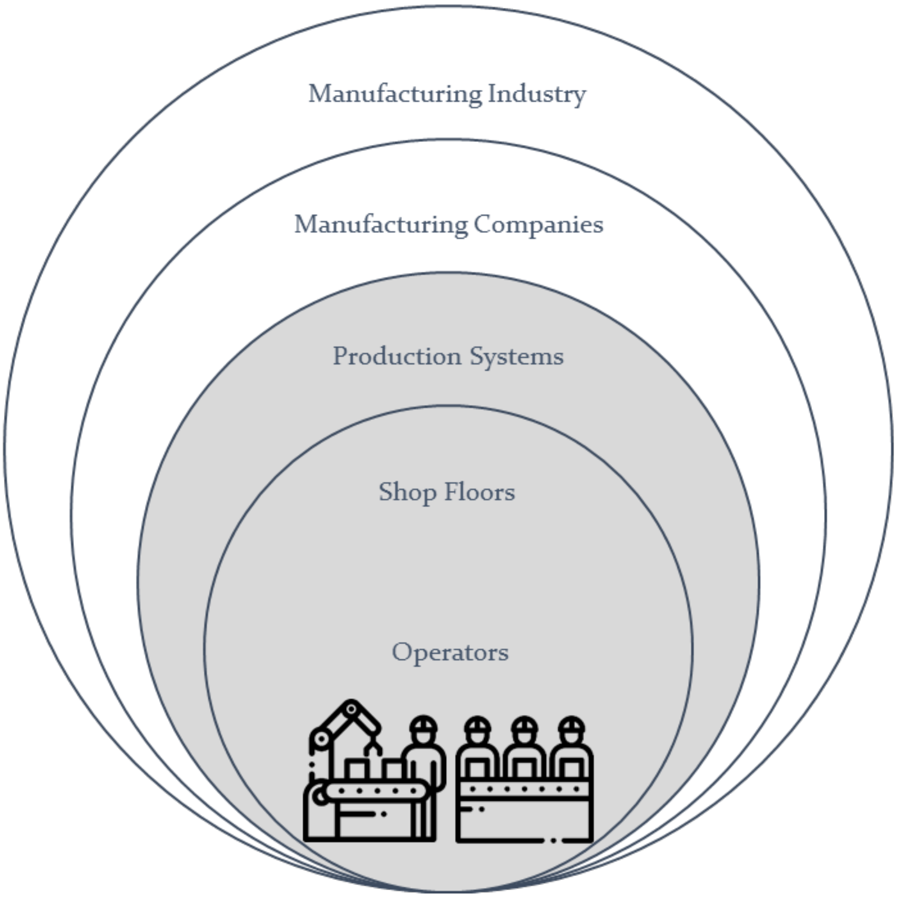
In terms of quality of information presented, using digital technologies allows information to be presented more effectively to shop-floor operators. Thus, digital technologies can support operators by reducing misunderstandings and ensuring a correct grasp of the information conveyed on shop floors.

In this context, digital technologies can present and visualize different types of information, such as assembly instructions. However, for digital technologies to be successfully implemented and be effective, the quality of information needs to be considered in terms of its intended users. Conducting experiments with operators allows their perception of the carrier and content of information to be assessed.

Hence, RQ2 focuses on the digital transformation from a shop-floor perspective, with the emphasis on cognitive support for Operator 4.0.

1.3 SCOPE AND DELIMITATIONS

Companies in the manufacturing industry use production systems involving final assembly. The focus of this thesis is on such final-assembly shop floors, in which human operators are important, as shown in Figure 1.1.

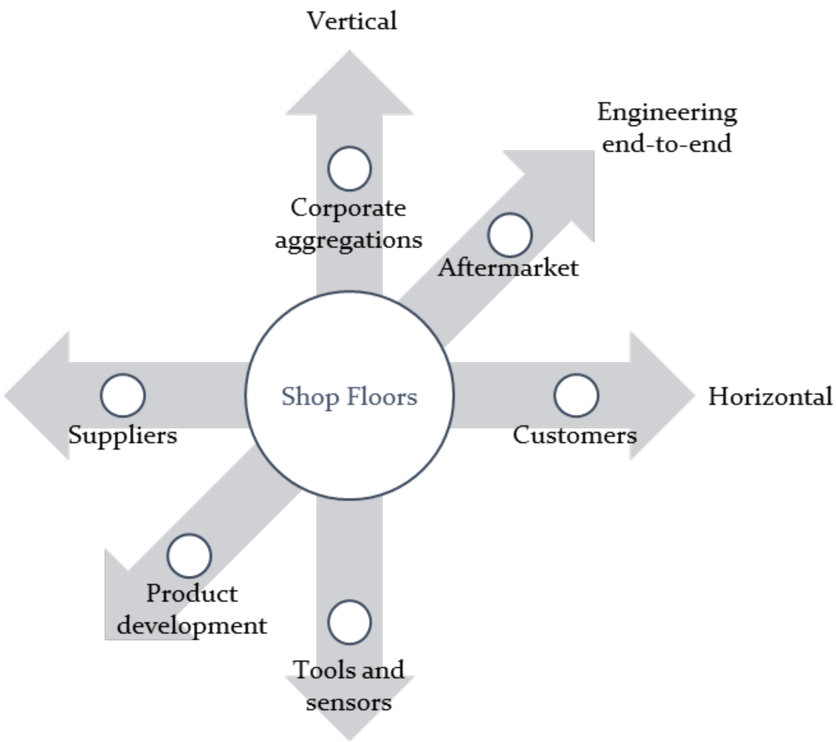


Information Sharing

Information flows in three dimensions. It flows to, within, and from shop floors:

- horizontally along the value chain, from suppliers, through shop floors, to customers (and vice-versa);
- end-to-end engineering, from product development, through shop floors, to maintenance and aftermarket (and vice versa);
- vertically, from tools and sensors, through shop floors and aggregated on corporate levels (and vice-versa).

This thesis recognizes the importance of these information flows but will not focus on these shop-floor-adjacent functions.



Maturing towards Industry 4.0

In terms of maturing towards Industry 4.0, four areas are important to this thesis in general and RQ1 in particular. These four areas, with their internal delimitations, are:

- resources. This thesis will include how resources manage information. However, the management and upskilling of resources will not be covered;
- information systems. This thesis will include the use of IT systems, their functionalities, and effects. However, programming and specific system architectures will not be covered (such as systems engineering and technical interoperability);
- organizational structure. This thesis will include how some organizational concepts may enable digital capabilities. However, business management aspects will not be covered;
- culture. This thesis will include how operator trust and willingness to change may affect digital maturity. However, change management concepts will not be covered.

Cognitive Support for Operator 4.0

In terms of cognitive support for Operator 4.0, the quality and usefulness of the information presented are important to this thesis in general and RQ2 in particular. However, as it emphasizes information quality, this thesis will not be discussing cognition in terms of the following factors:

- anthropology,
- psychology,
- linguistics,
- user experience,
- interaction design.

A Caveat on Comparisons

The conceptualizations of effectiveness or results are mainly compared within companies and between different states on a continuous improvement journey. This is to maintain a focus on internal improvements. All companies face different challenges in different circumstances, even if some of them are similar. Comparisons between companies should therefore be made wisely and mindfully. When such comparisons do appear in this thesis, they are intended to inspire understanding of what future developments might be attainable, rather than to judge either stakeholder.

1.4 OUTLINE OF THE THESIS

After this first chapter introducing the importance of this research, this thesis is structured into the following five chapters.

Chapter 2, Frame of Reference introduces the concepts and models needed to understand the relevant empirical results and subsequent analyses.

Chapter 3, Research Approach unpacks this thesis' scientific approach to the research and sets out the methods applied in this thesis and its appended papers.

Chapter 4, Summary of Appended Papers recapitulates the main outcomes of the five appended papers and their contributions to answering the research questions.

Chapter 5, Discussion combines the contributions of the five appended papers and elaborations and answers to the research questions are made, the implications for academic research and the manufacturing industry are laid out, and quality of the research and its limitations are reflected upon.

Chapter 6, Conclusion summarizes the major points of interest and offers final remarks on the research questions.

2

FRAME OF REFERENCE

This chapter starts with an introduction to the concept of information, followed by its effective sharing in production systems. The chapter goes on to explore the opportunities offered by Industry 4.0 and digitalization technologies.

2.1 INFORMATION IN PRODUCTION SYSTEMS

It can be difficult for organizations to distinguish the concepts of data, information, and knowledge from each other (Davenport and Prusak, 1998). Data and information can appear similar, as can information and knowledge. However, data and knowledge are quite different.

Data is a set of discrete and objective facts about events or objects (Davenport and Prusak, 1998; Tuomi, 1999). Data on its own is quite uninteresting as it offers no interpretation of these items. However, the importance of data lies in its role as the foundation for creating information (Drucker, 1988) through contextualization, categorization, calculation, correction, and condensation (Davenport and Prusak, 1998). In this sense, information is data that has been endowed with purpose and relevance (Drucker, 1988).

While information builds on data, knowledge may be viewed as built upon information (Ackoff, 1989; Rowley, 2007) by mixing it with experiences, values, and insights (Davenport and Prusak, 1998). This concept of relating data, information, and knowledge may be visualized as a spectrum, as in Figure 2.1. Unlike information, which is descriptive, knowledge is prescriptive (Ackoff, 1989) and heavily dependent on the belief and commitment of humans to understanding a given piece of knowledge (Nonaka, 1994). Hence, knowledge is based on human understanding and, within an organization, can only be created by individuals (Nonaka, 1994; Crossan et al., 1999) through comparisons, consequences, connections, and conversations (Davenport and Prusak, 1998).

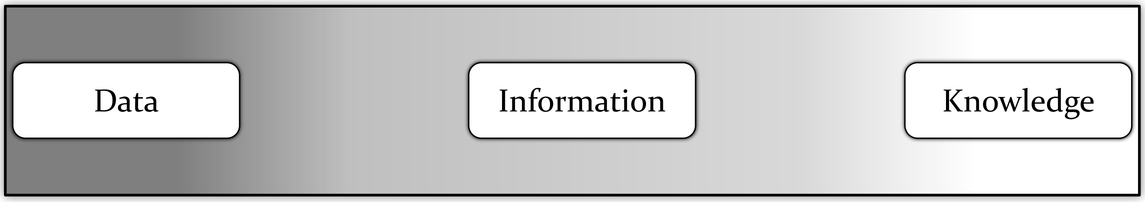


Figure 2.1. Spectrum of data, information, and knowledge.

Data, Information, and Knowledge in a Shop-floor Context

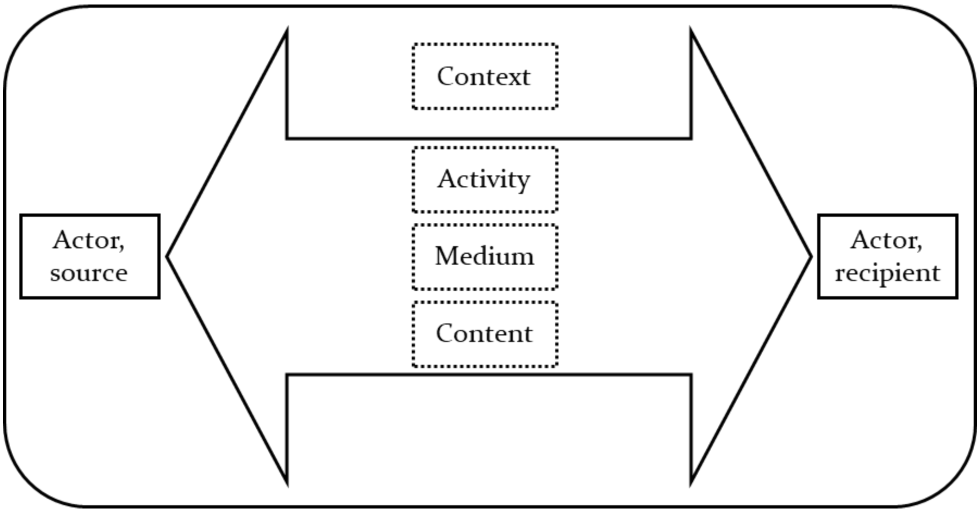
The above conceptualizations of data, information, and knowledge may be further deliberated upon in a shop-floor context. The following characterizations may be made:

- data may be considered to be the many new data points from sensors connected to the Industrial Internet of Things (Åkerman et al., 2018; Bärring et al., 2020);
- information includes assembly instructions for operators and dashboards that support shop-floor meetings (Johansson et al., 2018; Li et al., 2018b);
- knowledge encompasses the experiences and know-how of operators and other stakeholders (Nonaka, 1994; Paulin, 2006).

However, as shown earlier in Figure 2.1, there are no clear delimitations between data and information, or between information and knowledge. Rather, there is a transitional grey area (Davenport and Prusak, 1998; Rowley, 2007). An example is the aggregated shop-floor data which functions as decision support; this may be viewed as both data and information. Another example is the codification of operators' procedural experiences, which may be considered to be both information and knowledge.

2.2 INFORMATION SHARING

Shannon and Weaver's (1949) communication model explains how information is shared between individuals. It emphasizes the sender and receiver without giving attention to feedback loops between the individuals during the information-sharing activity. Figure 2.2 presents a model of information sharing by Paulin (2013). This model synthesizes other models by Lindkvist (2001), Cummings and Teng (2003), Paulin (2006), Minbaeva (2007), and Duan et al. (2010) and is adapted for information-sharing activities in a manufacturing context.



In this model, the individuals participating in the information-sharing *activity* are referred to as *actors*. The information *content* is shared through a *medium* encompassing channels or carriers through which information is shared (face-to-face conversation or e-mail correspondence, for example). *Context* explains the situation in which information is shared. The five components of this model (activity, actors, content, context, and medium) have associated factors that influence information sharing (Paulin and Winroth, 2013).

Dissemination and Presentation of Information

To clarify the research context, the term *information sharing* encompasses the many approaches to how information travels, so that the information content exists for both source and recipient actors (Sahin and Robinson, 2005). Thus, in this thesis, *information sharing* is further divided into the following two categories:

- Disseminating information, which is the focus of RQ1, encompasses how information travels from source actors so that it becomes available to recipient actors (Tih et al., 2016). Metaphorically, it may be likened to repeated broadcasting (Peters, 2006). Here, the effectiveness focuses on the expediency of the dissemination.
- Presenting information, which is the focus of RQ2, encompasses how information is internalized by the senses of recipient actors (Kester et al., 2001; Sarter, 2006). Here, the effectiveness focus on the quality of the information content itself.

Cognitive Automation

Cognitive processes may be categorized as *intuition* and *reasoning* (Kahnemann and Krueger, 2006). While intuitive cognitive processes are often automatic, effortless, and fast (Tsujii and Watanabe, 2009), reasoning is more explicit and requires operators to have analytical skills (Evans, 2003; Tsujii and Watanabe, 2009). To support operators cognitively will require different approaches depending on the situation; whether operators need to intuit, reason, or both.

By using technical solutions to help operators understand which work tasks to carry out and how to do them, operators may be supported cognitively in their work tasks (Thorvald et al., 2019). Such technical solutions, or digitalization technologies, are referred to as "cognitive automation" (Fast-Berglund and Stahre, 2013).

From a shop-floor perspective, factors including willingness to change (Bovey and Hede, 2001), trust (Lee and See, 2004), and culture (Mohelska and Sokolova, 2018) become increasingly important if cognitive automation is to be used (Parasuraman and Riley, 1997).

Quality of Information

When sharing information, the actors participating in the activity may have differing perceptions of the content. For cognitive automation to support operators, the quality of its information content is important (DeLone and McLean, 2003; Petter et al., 2013). Kehoe et al. (1992) presented six different attributes that affect the quality of shared information:

- relevance – is it useful?
- timeliness – is it presented when needed?
- accuracy – is it correct?
- accessibility – is it easy to find?
- comprehensiveness – is it enough to act on?
- format – is it easy to understand?

In a manufacturing industry context with assembly instructions, these quality attributes may be concretized into five situational aspects, all of which need to be attained for the instructions to be suitable for operators (in terms of a match between the instructions that are needed and those that are received (Haug, 2015)):

- complete,
- unambiguous,
- needed,
- correct,
- adequate repetitions.

Codification and Personalization Strategies

As presented earlier, sharing different kinds of information may take different forms or shapes for different people. Hansen et al. (1999) offer insights into managing information within organizations, focusing on the components of activity and medium from Figure 2.2. They do this by introducing two strategies; codification and personalization. Their respective characteristics are listed in Table 2.1.

Table 2.1. Codification and personalization strategies with their characteristics, adapted from Hansen et al. (1999).

Characteristics	Codification strategy	Personalization strategy
Strategic focus	People-to-documents. Develop IT systems that codify, store, and disseminate information.	Person-to-person. Develop networks, communities, and arenas for people to share information.
Information technology requirements	Need to make it simple for people to find relevant information or documents.	Need to make it simple for people to connect with other people.
Anthropocentricity	People need to develop skills in finding information in IT systems. People who are actively documenting in the IT systems are rewarded.	People need to develop skills for social interaction. People who actively interact with other people are rewarded.
Potential benefits	Process control, visibility, traceability, etc.	Collaboration, participation, problem-solving, etc.

The codification strategy relies on documentation, which requires a system for people to store information accessibly (Hansen et al., 1999). The personalization strategy relies on face-to-face interactions; these require a network of people who frequently exchange predominately tacit knowledge (Hansen et al., 1999). McMahon et al. (2007) conclude that neither strategy will satisfy organizations on their own, since their benefits depend on the situation. Each strategy should be deployed and adapted to each situation.

2.3 INDUSTRY 4.0

Although not yet a fully consolidated term (Pereira and Romero, 2017), Industry 4.0 has garnered attention from practitioners and researchers alike (Liao et al., 2017; Xu et al., 2018). In this context, the manufacturing industry is proactively (Almada-Lobo, 2015) undergoing a technology-driven (Lasi et al., 2014) paradigm shift (Yao and Lin, 2016) towards increased digitization, automation, and communication (Oesterreich and Teuteberg, 2016).

From a technological perspective, the dissemination of information is enabled by interoperability and integration of IT systems (between sensors, IoT platforms, and dashboards, for example) (Lasi et al., 2014; Yao and Lin, 2016; Xu et al., 2018; Alcácer and Cruz-Machado, 2019).

In this Industry 4.0 context, data is becoming more and more valuable as it supports better decision-making (Bärring et al., 2018; Berinato, 2019) in many areas; including but not limited to enabling robust maintenance (Lundgren et al., 2018), improving operational flexibility (Salunkhe and Fast-Berglund, 2020), or creating new services (González Chávez et al., 2021). This is especially so because information and knowledge build upon data (Ackoff, 1989; Davenport and Prusak, 1998; Rowley, 2007). This leads to a greater digital bidirectional integration of data, information, and knowledge across three dimensions (Kagermann et al., 2013; Leyh et al, 2016), as illustrated in Figure 1.2:

- horizontal integration through value networks;
- end-to-end digital integration of engineering across the entire value chain;
- vertical integration and networked manufacturing systems.

These integrations are enabled by the interoperability between the various IT systems in production systems (Åkerman et al., 2018). However, it is still difficult for many companies to implement digital technologies related to Industry 4.0 for such purposes (Bittighofer et al., 2018; Chengula et al., 2018; Stentoft et al., 2019). This provides opportunities for research into Industry 4.0.

Assembly Systems 4.0

Industry 4.0-enabling technologies support the digitalization of the manufacturing industry. Bortolini et al. (2017) list six characteristics of Assembly Systems 4.0. In other words, assembly work impacted by implementing Industry 4.0-enabling technologies:

- aided assembly,
- intelligent storage management,
- self-configured workstation layout,
- product and process traceability,
- late customization,
- assembly control system.

Maturity or Readiness for Industry 4.0

For companies to make a digital transformation (that is, to embrace parts of Industry 4.0 and its related technologies), they need to assess their current situation (Peukert et al., 2020), based on either its readiness or maturity (De Carolis et al., 2017). While readiness models should be used before transformations are undertaken, maturity models aim to assess the situation as-is during them (Schumacher et al., 2016). Hence, readiness models focus on whether a company or certain technologies are ready for implementation, while maturity models focus on companies' progress along a transformation journey (Machado et al., 2019). Further, maturity models can help reflect on current capabilities regarding Industry 4.0 and subsequent decisions as to strategies and action plans (Schumacher et al., 2016).

The companies in this thesis have already implemented certain digitalization technologies and have thus already begun transforming towards implementing Industry 4.0 concepts. Therefore, maturity models are preferable to readiness ones.

For the above reasons, the Industrie 4.0 Maturity Index (Schuh et al., 2017; Schuh et al., 2020a; Schuh et al., 2020b) was selected as the model for evaluating and assessing the digital maturity of production systems. It is based on the following factors:

- its emphasis on information sharing, with less emphasis on technology. This aligns with the purpose of this thesis in determining the implications of information sharing, thus eliminating the models by Rockwell Automation (2014), Anderl et al. (2015), and Leyh et al. (2017), which focus on technical aspects or business models (Mittal et al., 2018; Kolla et al., 2019);
- its comprehensiveness, enabling follow-up discussions and providing rich empirical data. This eliminates the models by Lichtblau et al. (2015) and Geissbauer et al. (2015), which consist of simpler self-checks for companies (Schumacher et al., 2016; Colli et al., 2019);
- its capacity to adapt and focus on shop-floor operators' involvement in how information is shared in final assembly. This eliminates the model by Schumacher et al. (2016), which focuses on the manufacturing machinery (Schumacher et al., 2016).

Industrie 4.0 Maturity Index

For companies to assess their Industry 4.0 proficiency, Schuh et al. (2017) introduced the Industrie 4.0 Maturity Index. It supports an Industry 4.0 roadmap journey, whereby functional areas of a company, such as production or logistics, are assessed. This model was later refined (Zeller et al., 2018; Schuh et al., 2020a) and complemented with company examples (Schuh et al., 2020b).

A company's maturity is assessed against six possible stages. The model does not imply that achieving a high maturity stage must be short or long-term goals for a company. It allows maturity stages to be identified for individual processes, or specific parts of a shop floor. To date, 70 cases in Germany have been assessed. The results indicate that 80% of those cases are positioned at connectivity (stage 2), with no company achieving transparency (stage 4) (Schuh et al., 2020b).

This model proposes four structural areas of assessment, each with two guiding principles:

- *Resources* comprise employees and all necessary production factors. These communicate as smart objects with each other and subdivide into the principles of *structured communication* and *digital capability*;
- *Information systems* comprise integrated systems. These capture data and information, process it, and provide it with a context and subdivide into the principles of *information processing* and *integration of IT systems*;
- *Organizational structure* enables effective and secure collaboration along the entire value chain and subdivides into the principles of *organic internal organization* and *dynamic collaboration in value networks*;
- *Culture* in a company supports a mindset of continuous learning and improvement and subdivides into the principles of *social collaboration* and *willingness to change*.

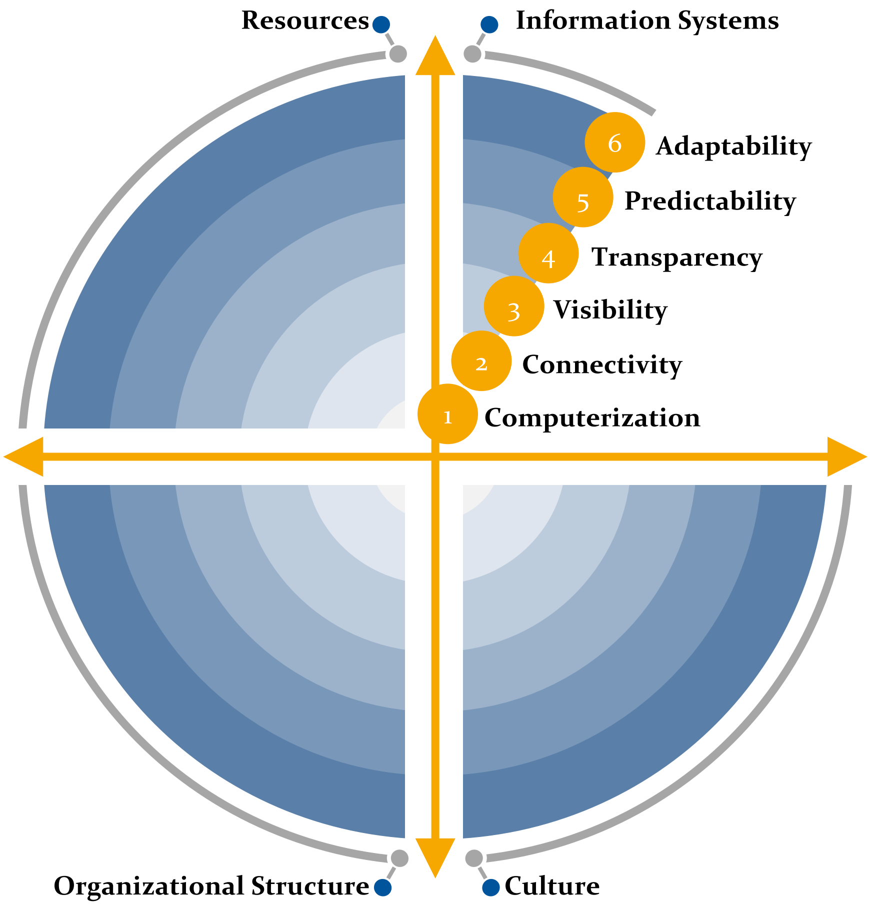


Figure 2.3. Industrie 4.0 Maturity Index, with its four areas and six stages, adapted from Schuh et al. (2017).

Company maturity relating to the structural areas' guiding principles is assessed based on the maturity stages of the Industry 4.0 development path, as illustrated in Figure 2.3.

While Schuh et al. (2017) include stages 1-6, each one must be accomplished before moving onto the next stage. Paper II also included a stage 0, as some cases had not yet reached stage 1. stage 0 comprises non-computerized means of communication. These are dominated by word of mouth (for transferring information) and pen and paper (for documenting it).

For each of the eight aforementioned principle areas, the quantitative assessment of the maturity levels is based on these descriptions of the six stages:

1. *Computerization* describes the use of information technologies for all a company's running processes. This includes working on and documenting the scheduling, organization, and operations tasks. Data and information are thereby stored centrally and become available for analysis.
2. *Connectivity* refers to the condition whereby the various resources and processes are connected through interfaces. Isolated records and processing of data and information only occur in exceptional cases. This helps avoid media disruptions and information loss.

3. *Visibility* enables the first real benefit propagated by Industry 4.0; the achievement of information and decision accessibility within a business process. All a factory's actions are comprehensively documented and can be observed in near real-time.
4. *Transparency* amplifies the question of what is happening into the question of how and why something is taking place in a company. This expanded understanding may be used to construct an extensive expert system.
5. *Predictability* converts this expert knowledge into predictions. Relevant models are used to target future system conditions and provide mechanisms to support decision-making. The decision processes become even faster and more robust.
6. *Adaptability* describes the greater autonomy of these decision processes. Up to a certain point, alternatives are generated and evaluated automatically. Ultimately, those that seem most appropriate are put into practice.

2.4 OPERATOR 4.0

Human operators remain important stakeholders, contributing to the overall success of production systems (Guimaraes et al., 1999; ElMaraghy, 2006; Griffin et al., 2007; Hu et al., 2011; Toro et al., 2015). The combination of increasingly automated and complex manufacturing systems means that problem-solving humans at work must be flexible and manage a variety of tasks and technologies (Jensen and Alting, 2006; Toro et al., 2015). Alongside managing this complexity (ElMaraghy et al., 2012), human operators are vital to interaction and initiatives (Kagermann et al., 2013), coordination and problem-solving (Brettel et al., 2014), and decision-making (Stankovic, 2014). On future shop floors, these skilled human operators Operator 4.0, can and should be aided, both cognitively and physically (Romero et al., 2016; Rauch et al., 2020).

Technology is an important enabler of collaboration between people (Blankenburg et al., 2013; Aranda Muñoz et al., 2021; ElMarahgy et al., 2021) and recent developments have greatly benefitted a more rapid sharing of information and knowledge (Inkinen, 2016). Apart from technologies specifically designed for communication, the incoming paradigm shift in the manufacturing industry, *Industry 4.0*, will also create new sources of valuable data, information, and knowledge (Lasi et al., 2014). In this context, it is becoming increasingly important for companies to have purposeful strategies for managing data (DalleMulle and Davenport, 2017), information (Petter et al., 2013), and knowledge (Toro et al., 2015).

Despite increased digitization and automation in Industry 4.0 (Oesterreich and Teuteberg, 2016), humans are as important as ever in the manufacturing industry (Brettel et al., 2014; Stankovic, 2014; Longo et al., 2017; Taylor et al., 2020). However, most research into Industry 4.0 concerns technological aspects and possibilities (Kagermann et al., 2013; Lasi et al., 2014; Liao et al., 2017). To underline the importance of designing the manufacturing industry to support human operators, Romero et al. (2016) propose emphasising Operator 4.0. This idea has also garnered attention from other researchers (Mattsson et al., 2018a; Taylor et al., 2020; Kaasinen et al., 2020). Romero et al. (2016) outline eight typologies in which Operator 4.0 may be supported. Five of these are solely a matter of cognitive automation and are listed in Table 2.2.

Table 2.2. Operator 4.0 typology with cognitive interaction, adapted from Romero et al. (2016).

Operator 4.0	Interaction	Short description
Augmented operator	Cognitive	Augmented reality technology overlaying information for the operator.
Virtual operator	Cognitive	Virtual reality technology with immersive simulations that can support decisions.
Smarter operator	Cognitive	Intelligent personal assistants can help operators manage tasks and interact with automation.
Social operator	Cognitive	Social networks help operators create communities. This promotes the sharing of information and knowledge.
Analytical operator	Cognitive	Big data analytics help operators make better data-driven decisions.

As the manufacturing industry gets more complex (Hu et al., 2011; ElMaraghy et al., 2012), so the work of the operators does (Jensen and Alting, 2006; Toro et al., 2015). This comes into play because a strategic consensus between operators and managers is important to the content of a manufacturing strategy (Edh Mirzaei et al., 2016). Applying a human-centred approach to production development by involving operators has many positive effects on continuous improvement efforts (Longoni and Cagliano, 2014; Lam et al., 2015). This is especially the case if valuable knowledge and experience can be elicited and disseminated (Tamayo-Torres et al., 2014; Brennan et al., 2015).

Operator 4.0 can and should be supported cognitively (Romero et al., 2016; Mattsson et al., 2018a) through such things as training and planning using virtual reality technology (Gorecky et al., 2017; Eriksson et al., 2020; Nåfors et al., 2020), or personalized instructions based on work experience (Johansson et al., 2018). Even though many new technologies are being developed and off-the-shelf solutions are available, it is still difficult to implement technologies that support operators (Stentoft et al., 2019). Often, this is because an automation solution is not implemented in a way that would encourage people to work with automation (Parasuraman and Riley 1997). One aspect for companies to consider when implementing support systems for operators should be individual needs and information preferences (Haghi et al., 2018). The information can then be presented in a manner that is visually appealing or palatable to the operators (Thoben et al., 2017). This, in turn, demands that an organization should involve its operators in design processes (Bauer et al., 2017).

3

RESEARCH APPROACH

This chapter connects the epistemological considerations of the research to the pragmatic, mixed-method approach applied in this thesis. It also outlines the specific methods applied in the five appended papers.

3.1 EPISTEMOLOGICAL REFLECTIONS

In this thesis, knowledge has been defined as enriched information, as shown in Figure 2.1 (Ackoff, 1989; Davenport and Prusak, 1998; Rowley, 2007). This type of information-based knowledge is often shared on shop floors, whether among operators, managers or other stakeholders in the manufacturing industry (Drucker, 1988). The operators themselves often describe such knowledge as a “gut feeling” or that they simply know how to conduct certain work (Davenport and Prusak, 1998; Li et al., 2018b). The definition of this knowledge may be simplified as “experience-based tacit knowledge” and is often subjective, depending on the eye-of-the-beholder (Polanyi, 1966).

However, another approach to describing knowledge may be conceptualized as *justified true belief* and is often ascribed to Plato (360 BCE) in his dialogue *Theaetetus*. This definition of knowledge is illustrated as a Venn diagram in Figure 3.1. Subject ***S*** knows that proposition ***P*** is true, if and only if:

- ***P*** is true,
- ***S*** believes that ***P*** is true, and
- ***S*** is justified in believing that ***P*** is true.

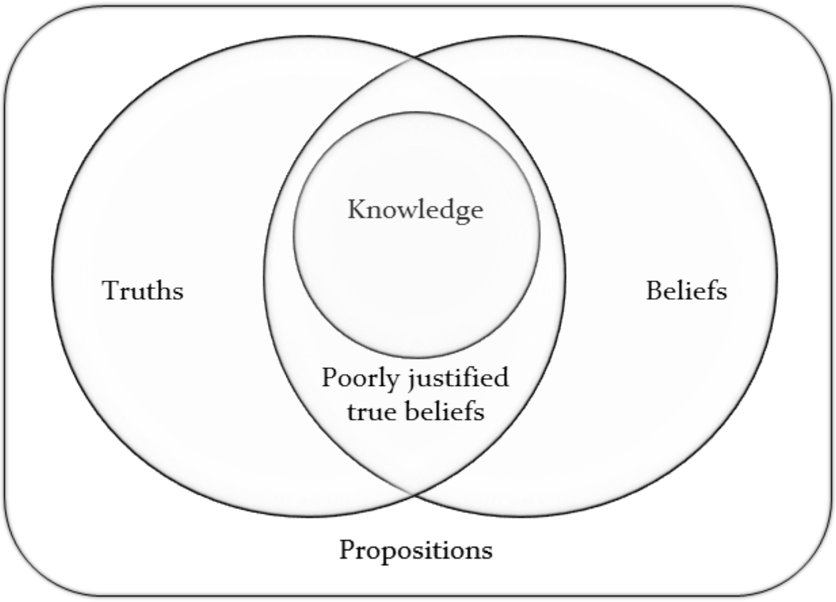


Figure 3.1. Venn diagram of knowledge as justified true belief, adapted from Li (2019).

This definition of knowledge has been criticized. For example, an individual may be justified in believing that a specific piece of knowledge piece is true based on false premises (Gettier, 1963). Similarly, defining knowledge as a higher level of understanding derived from human minds at work and built on information, experiences, values, and insights (Ackoff, 1989; Davenport and Prusak, 1998) offers some explanation as to the basis of given justifications and beliefs. This knowledge can be simplified as "fact-based explicit knowledge", which should be objective in its scientific context (Ribeiro, 2013).

Whether experience-based tacit knowledge or fact-based explicit knowledge, both approaches to defining knowledge essentially point towards the same thing; that justification and belief correspond to uninterpreted facts given meaning and context, then mixed with experience and insight to become knowledge.

These epistemological reflections highlight two approaches to the concept of knowledge. First, the experience-based tacit knowledge that resides with and can be shared amongst shop-floor operators. Second, the fact-based explicit knowledge created by studying operators who share knowledge (Creswell and Plano Clark, 2018). This may be further described as formal knowledge or systematic insight into processes (Davenport and Prusak, 1998). It is to this general body of knowledge about production systems that this thesis contributes.

3.2 RESEARCH PHILOSOPHY AND APPROACH

In contributing to the general body of knowledge about production systems, a pragmatic approach to applied research (of instrumentalism philosophy and mainly abductive reasoning) has guided the selected mixture of quantitative and qualitative research methods.

Due to the nature of the objects being studied (essentially how people and their behaviour may be supported in a production system), this thesis has taken a pragmatic approach to applied research. By contrast, there is basic research, which focuses on theory-building and hypothesis-testing (Williamson, 2002) which uphold a coherence theory of truth, with findings that rationally, logically, and consistently fit into existing truths and prior knowledge (Lehrer and Cohen, 1983). Applied research strives to solve specific problems in specific situations (Williamson, 2002). A pragmatic approach to applied research denotes a "whatever works" attitude in explaining how problems were solved (Creswell and Plano Clark, 2018). This shifts the focus of the research from asking "why" to asking "how" and "what". In this context, this thesis maintains an instrumentalism philosophy, in which the scientific contribution does not ask to be judged on its ability to provide absolute truth but rather on its effectiveness (Knowles, 2006). In other words, the usefulness of the frameworks and models in explaining events and generating predictions that can be confirmed with empirical data.

In the process of systematic investigation to acquire new knowledge, inductive and deductive reasoning describe two strategies of scientific inquiry. While inductive reasoning focuses on analysing empirical data to build theory, deductive reasoning focuses on testing hypotheses to confirm or reject theory (Bryman and Bell, 2011). However, in the spirit of instrumentalism and pragmatism, this thesis has been guided mainly by a third strategy, abductive reasoning, or inferring the best explanation. Unlike deductive reasoning, abductive reasoning deals with plausibility and likelihood rather than outright confirmation or rejection (Knowles, 2006).

3.3 RESEARCH ACTIVITIES

The research activities in this thesis and its appended papers were conducted between 2016 and 2021 in five research projects; four funded by *Vinnova* (the *Swedish Governmental Agency for Innovation Systems*) and one by the *Swedish National Space Agency*:

- 2016-2018: Global Assembly Instruction Strategies 2 (GAIS2)
- 2016-2018: MEET-UP
- 2017-2020: Demonstrating and Testing Smart Digitalization for Sustainable Human-Centred Automation in Production
- 2019-2021: Instruction Innovation for Cognitive Optimisation (TACO)
- 2019-2021: Future Manufacturing of Space Components II

The alignment of the appended papers with the research questions is shown in Table 3.1, plus the principal duration of the research activities.

Table 3.1. Research activities and their alignment with the appended papers.

	Paper I	Paper II	Paper III	Paper IV	Paper V
RQ1	**Major contribution**	**Major contribution**	Minor contribution	**Major contribution**	Minor contribution
RQ2		Minor contribution	**Major contribution**	Minor contribution	**Major contribution**
Research activities conducted	2018-2019	2018-2019	2017-2019	2019-2020	2017-2020

3.4 RESEARCH DESIGN AND DATA COLLECTION

Based on the pragmatic approach and abductive reasoning in general, a variety of methodologies were applied in these research projects and their outcomes (in the form of the appended papers).

Papers I, III, and V used qualitative research methods, while Papers II and IV used mixed-methods research, combining qualitative and quantitative methods in different sequences (Creswell and Plano Clark, 2018), as outlined in Table 3.2.

Paper I used a systematic literature review (Snyder, 2019), in which 178 articles were identified and collected. This was followed by an appraisal, with 163 articles excluded and the remaining 15 articles analysed in full. The contents of these 15 articles were synthesized.

Paper II used a thematic analysis approach (Braun and Clark, 2006). First, 15 structured interviews were conducted across three cases. This was followed by a thematic analysis, in which a quantitative assessment of the interview results was conducted.

Paper III used a deductive approach to qualitative content analysis (Finfgeld-Connett, 2013). Based on a previously examined topic, qualitative data analysis began with a coding template in mind. In this case, three categories of assembly modes and data were organized according to an existing structure. The structure could be adjusted to test, adapt, expand, and improve upon the relevance and validity of existing frameworks.

Paper IV used a thematic analysis, building upon the outcome of Paper II (Braun and Clark, 2006), followed by an explanatory sequential method (Creswell and Plano Clark, 2018). The thematic analysis was based on a larger collection of data in comparison to Paper II. This enabled the explanatory sequential research design that followed, in which the quantitative assessment could be compared and explained across eight cases.

Paper V used comparative case studies (Yin, 2009). Five cases were developed independently, but their outcomes were compared according to the same criteria.

Table 3.2. Research design and data collection for the appended papers.

Paper	Research design and analysis	Intent of research design	Data collection
I	**Systematic literature review** Identification and collection, followed by appraisal and analyses	To synthesize research findings in a systematic, transparent, and reproducible way (Snyder, 2019)	178 abstracts from articles 15 articles in full
II	**Thematic analysis** Qualitative, followed by quantitative assessment	To quantify qualitative data for comparisons to identify themes or patterns (Braun and Clark, 2006)	3 industrial studies containing: 15 structured interviews
III	**Deductive content analysis** Qualitative review of theoretical content, followed by model development	To develop knowledge and generate theory based on integration, interpretation, synthetization of findings across multiple studies (Finfgeld-Connett, 2013)	36 articles
IV	*First* **Thematic analysis** Qualitative, followed by quantitative assessment	To quantify qualitative data for comparisons to identify themes or patterns (Braun and Clark, 2006)	8 industrial studies comprising: • workshops with 17 participants • 43 semi-structured interviews • 8 gemba walks, with observations and 25 unstructured interviews
	Then **Explanatory sequential** Quantitative, then qualitative, followed by interpretation	To use a qualitative strand to explain initial quantitative results and develop a strong explanation (Creswell and Plano Clark, 2018)	
V	**Comparative exploratory case studies** Qualitative cases, followed by qualitative comparisons	To compare the outcome of multiple qualitative cases (Yin, 2009)	5 industrial cases Unstructured interviews

3.5 RESEARCH QUALITY

Research validity relates to whether or not the research methods in question investigate what was intended (Yin, 2009). Research reliability refers to the lack of serendipity in collected empirical data; ensuring that the outcome was not a coincidence (Yin, 2009). This requires systematic rigour in controlling factors that may affect the outcome and, in turn, contributes to the trustworthiness of the research.

Trustworthiness

Research trustworthiness refers to the establishment of its four aspects (Lincoln and Guba, 1985):

- credibility, confidence in the "truth" of the findings;
- transferability, showing that the findings have applicability in other contexts;
- dependability, showing that the findings are consistent and could be repeated;
- confirmability, a degree of neutrality or the extent to which the findings of a study are shaped by the respondents and not researcher bias, motivation or interest.

Credibility was supported by member checks in Papers II, IV, and V, in which research outcomes were shown to the participants from whom the data was originally obtained (Lincoln and Guba, 1985). Data sources in Papers I and III were based on published articles. Two other techniques were applied to further support the credibility; persistent observation with a focus on detailed problem-solving in Paper II and prolonged engagement with enough time spent with the case companies in Papers IV and V.

Transferability was supported by thick descriptions (Lincoln and Guba, 1985) throughout the appended papers. By providing sufficiently detailed descriptions of phenomena in Papers I-V, conclusions drawn in the earlier appended papers could be transferred to the latter appended papers (despite differences in times, settings, situations, and people).

Dependability, similar to reliability, was supported by inquiry audits throughout the appended papers. Such external audits provided an opportunity for non-involved researchers to evaluate the accuracy of the research and whether the research outcomes were supported by the data (Lincoln and Guba, 1985). Paper I was subjected to a single-blind peer-review process and Papers II and III were subjected to double-blind peer-review processes. Papers IV and V are undergoing double-blind peer-review processes.

Confirmability, similar to, was supported by method triangulation, using qualitative and quantitative methods in Papers II and IV and investigator triangulation in Papers I-V (Lincoln and Guba, 1985).

4

SUMMARY OF APPENDED PAPERS

This chapter summarizes the five appended papers sequentially and recapitulates their contributions.

4.1 CONTRIBUTION OF THE APPENDED PAPERS

This thesis is scoped to focus on how digitalization has facilitated effective information sharing, as shown in Papers I-V.

Paper I commences the research outcome with a systematic literature review. This proposes the two research directions and is followed by RQ1 and RQ2. Papers II and III initiate the research efforts, problematize, and make major contributions to RQ1 and RQ2, with minor contributions to the other issues raised in this thesis. Papers IV and V build upon the outcomes of Papers II and III and provide empirical data upon which the answers to RQ1 and RQ2 are based. Table 4.1 summarizes the main outcomes of the appended papers and their contribution to the research questions.

Table 4.1. Summary of the main contributions from the appended papers.

Paper	Purpose	Main contribution to RQ1	Main contribution to RQ2
I	To propose research directions for effective cognitive support for Operator 4.0 in Industry 4.0.	**Major contribution.** First research direction. Organizations need strategies to identify and support individuals' needs for relevant information in Industry 4.0. This research direction motivates RQ1 of this thesis.	**Major contribution.** Second research direction. New solutions for visualising and presenting data, information, and knowledge need to be thoroughly tested. This research direction motivates RQ2 of this thesis.
II	To provide insights into current digitalization status and give an outlook for SMEs.	**Major contribution.** Assesses digital maturity of two SMEs and provides comparison with Assembly Systems 4.0 concepts.	Minor contribution. Examples of shared information.
III	To answer how cognitive automation solutions may be designed to support Operator 4.0 in complex assembly.	Minor contribution. Operators' needs place demands on new digital technologies.	**Major contribution.** Operators work in three different modes: learning, operative, and disruptive. Depending on operator situation, cognitive processes of reasoning, intuition, or both may need support.
IV	To evaluate the maturity of digitalized information sharing in terms of shop-floor capabilities.	**Major contribution.** Descriptive matrix of maturity and maturity assessments of seven cases.	Minor contribution. Digital maturity of production systems enables new information presentation capabilities.
V	To compare and evaluate different solutions for presenting information to Operator 4.0	Minor contribution. Exemplifies how some aspects of digital maturity may be increased. Need for new capabilities to enable presenting information to gain greater Industry 4.0 maturity.	**Major contribution.** Comparison and evaluation of different approaches to presenting information. This raises the possibility of selecting a suitable solution, depending on the circumstances of the assembly work and cognitive support needed.

4.2 PAPER I

Title: **Human-Centred Dissemination of Data, Information and Knowledge in Industry 4.0**

Short Description

Using a systematic literature review, this paper examines the relationship between:

- existing literature on the dissemination of data, information, and knowledge within the manufacturing industry and;
- state-of-the-art research into Industry 4.0 from a human-centred perspective.

The Scopus database rendered 178 documents when searching for titles, abstracts, and keywords containing:

- dissemination or transfer or sharing and
- data or information or knowledge and
- *Industry 4.0* or *Industrie 4.0*.

The abstracts of these 178 documents were then systematically reviewed using the following exclusion criteria:

- IT or system architecture without human aspects,
- security and data privacy,
- machine-to-machine communication,
- contexts other than manufacturing.

After these exclusions, the 178 documents were narrowed down to 15 articles. These were reviewed in full.

Main Results

The 15 articles are listed in Table 4.2. Based on a thematic analysis of their content, the 15 articles could be separated into four thematic areas (TA1, TA2, TA3, and TA4). Based on their content (and listed in order of first publication), these areas have implications for designing the dissemination of data, information, and knowledge:

- TA1: technological solutions or their use,
- TA2: learning and training,
- TA3: challenges and issues within Industry 4.0,
- TA4: organizational aspects of Industry 4.0.

Table 4.2. List of reviewed articles in Paper I and their themes.

Reference	Type	Thematic area based on article content
Scheuermann et al. (2015)	Conference article	Technological solutions or their use (TA1)
Alexopoulos et al. (2016)	Journal article	Technological solutions or their use (TA1)
Posselt et al. (2016)	Conference article	Learning and training (TA2)
Scheuermann et al. (2016)	Conference article	Technological solutions or their use (TA1)
Gorecky et al. (2017)	Journal article	Technological solutions or their use (TA1) **and** Learning and training (TA2)
Kinkel et al. (2017)	Conference article	Technological solutions or their use (TA1) **and** Learning and training (TA2)
Thoben et al. (2017)	Journal article	Challenges and issues within Industry 4.0 (TA3)
Aromaa et al. (2018)	Conference article	Technological solutions or their use (TA1)
Bauer et al. (2018)	Conference article	Organizational aspects of Industry 4.0 (TA4)
Haghi et al. (2018)	Conference article	Challenges and issues within Industry 4.0 (TA3)
Johansson et al. (2018)	Conference article	Learning and training (TA2)
Li et al. (2018b)	Conference article	Organizational aspects of Industry 4.0 (TA4)
Marinagi et al. (2018)	Conference article	Challenges and issues within Industry 4.0 (TA3)
Mourtzis et al. (2018)	Conference article	Technological solutions or their use (TA1)
Kaasinen et al. (2020)	Journal article	Challenges and issues within Industry 4.0 (TA3)

The four thematic areas, derived from these 15 reviewed articles, focus on various aspects of disseminating data, information, and knowledge in an Industry 4.0 context.

TA1 (seven articles). New technological solutions for information dissemination provide cognitive support to operators in different ways (Scheuermann et al., 2015; Alexopolous et al., 2016; Scheuermann et al., 2016; Gorecky et al., 2017; Kinkel et al., 2017; Aromaa et al., 2018; Mourtzis et al., 2018). This is important to operators' performance as work tasks are becoming more creative (Taylor et al., 2020) and will require other types of cognitive support in different situations (Romero et al., 2016). Hence, this array of cognitive support systems adds a flexibility that can help reduce complexity for operators (Jovane et al., 2003; ElMaraghy et al., 2012). However, implementing such support tools remains a challenge (Chengula et al., 2018; Stentoft et al., 2019).

TA2 (four articles). Learning and training opportunities for humans in manufacturing are also important to the dissemination of data, information, and knowledge in Industry 4.0 (which can be supported by its enabling technologies). Training may take place in a virtual environment (Gorecky et al., 2017) or at learning factories, with different sensors and actuators used to provide feedback to the trainee (Posselt et al., 2016). Using learning factories and demonstrators is also a useful tool for testing and verifying how different technologies may be used (Johansson et al., 2018) and how the above challenges may be addressed.

TA3 (four articles). Industry 4.0-enabling technologies are presenting organizations with new challenges. Most of the challenges discussed relate to technological problems. However, there is also an emphasis on challenges connected to identifying the relevant data (Haghi et al., 2018) and how to visualize it (Thoben et al., 2017). Understanding the needs of individual stakeholders (and the impact of those needs on the visual presentation of information) requires a more human-centred approach.

TA4 (two articles). Organizational aspects are important to the implementation of Industry 4.0-enabling technologies in general (Kagermann et al., 2013; Leyh et al., 2016), but become especially important when the focus is human-centred (Bauer et al., 2017; Li et al., 2018b). Cognitive support systems should effectively reduce complexity and help operators to solve problems (Brettel et al., 2014) and make decisions (Stankovic, 2014). In this context, organizational challenges include difficulties in understanding individuals' various needs (Rowley, 1998) and expectations (Parasuraman and Riley, 1997) regarding information content and presentation. Hence, disseminating data, information, and knowledge must be supported by organizational reconciliation and accommodation of those individual needs and expectations.

Discussion and Conclusion

Based on the four thematic areas, two research directions have been identified to advance the dissemination of data, information, and knowledge in Industry 4.0 contexts.

The first direction is based on TA1, TA2, and TA4. Organizations need strategies for identifying and supporting individuals' needs for relevant data, information, and knowledge, at the right place and right time. They also incorporate opportunities for Industry 4.0 to disseminate such data, information, and knowledge more effectively. This research direction contributes to RQ1 of this thesis.

The second direction is based on TA 1, TA2, and TA3. New solutions for visualising and presenting data, information, and knowledge must be thoroughly tested (conceptually and empirically) in company cases. This depends on the level of technological and organizational readiness. This research direction contributes to RQ2 of this thesis.

These two research directions go hand-in-hand, as digital transformation needs to consider both organizational and technological aspects of human-centred dissemination of data, information, and knowledge in Industry 4.0. Accomplishing this requires a holistic framework for identifying and accommodating individuals' needs and expectations of relevant data, information, and knowledge. Furthermore, there must be demonstrators and concepts to simplify the implementation of Industry 4.0-enabling technologies. These must support the aforementioned dissemination.

4.3 PAPER II

Title: **Current and Future Industry 4.0 Capabilities for Information and Knowledge Sharing**

Short Description

This paper provides insights into current digitalization efforts by SMEs and discusses possible near-future implementations of Industry 4.0-enabling technologies. The paper places both topics in an Industry 4.0 context, supporting the human-centred dissemination of information. Shop-floor operators and office workers at two Swedish SMEs were interviewed, to identify their current Industry 4.0 capabilities.

Current digitalization efforts are explored in terms of their Industry 4.0 maturity. The perspective of Operator 4.0 in Assembly Systems 4.0 plus future capabilities are both assessed under the same Industry 4.0 maturity framework.

Main Results

The results of the interviews are summarized in Table 4.3, with their respective maturity assessments. At Company A, shop-floor operators' work (Case A1) was predominantly communicated through word of mouth, complemented with some paperwork. Their office colleagues' (Case A2) information and knowledge-sharing activities were largely supported by computerized technologies but required manual work to transfer them. Company B's different locations largely necessitated a same-time, different-place approach. Therefore, its *resources* have a level of connectivity, raising it in one structural area to a maturity stage of 2.

The characteristics proposed by Bortolini et al. (2017) suggest a developmental direction for companies. Most relate to the structural area of information systems but resources and organizational structure are also affected. The companies studied in this paper are at stage 0 (pre-digitalization) for shop-floor operators and stage 1 (computerization) for office workers. Using Assembly Systems 4.0, the companies may reach stages 3, 4, or 5 for the different structural areas, as shown in Table 4.4. However, stage 6 (adaptability) may be further into the future.

Table 4.3. Summary of results and assessments of Industry 4.0 maturity stages in Paper II.

Resources			
Case	Digital capability	Structured communication	Stage
A1. Shop-floor operators	Word of mouth, yardstick measurement	Word of mouth	0
A2. Office workers	ERP system, emailing	Word of mouth, meeting notes on computer	1
B. Office workers	ERP system, service system, and connected spreadsheets	ERP system, phone calls for clarification only	2

Information systems			
Case	Information processing	Integration of IT systems	Stage
A1. Shop-floor operators	Work orders on paper	Word of mouth	0
A2. Office workers	ERP system, own contextualization	Emails, phone calls	1
B. Office workers	ERP system	Emails, phone calls, meeting notes on computer	1

Organizational structure			
Case	Organic internal organization	Dynamic collaboration in value networks	Stage
A1. Shop-floor operators	Word of mouth	Work orders on paper	0
A2. Office workers	Word of mouth, emails, phone calls	Word of mouth, emails, phone calls	1
B. Office workers	Word of mouth, emails, phone calls	Word of mouth, emails, phone calls	1

Culture			
Case	Willingness to change	Social collaboration	Stage
A1. Shop-floor operators	Show-and-tell	Work orders on paper, show-and-tell	0
A2. Office workers	Spreadsheet and calendar on computer	ERP system	1
B. Office workers	Word of mouth	Word of mouth	0

Table 4.4. Assessment of Assembly Systems 4.0 in relation to Industry 4.0 maturity stages in Paper II.

Assembly Systems 4.0 tool	Main structural areas affected	Stage of Industrie 4.0 Maturity Index
Aided assembly	Resources Information systems	Stage 3 - Visibility
Intelligent storage management	Information systems	Stage 4 - Transparency
Self-configured workstation layout	Information systems	Stage 4 - Transparency
Product and process traceability	Information systems	Stage 4 - Transparency
Late customization	Resources Organizational structure	Stage 5 - Predictability
Assembly control system	Information systems	Stage 5 - Predictability

Discussion and Conclusion

The studied companies' current production-related practices for sharing information and knowledge are currently at a pre-Industry 4.0 maturity stage in regard to structural areas (resources, information systems, organizational structure, and culture). In other words, Industry 4.0-enabling technologies capable of visibility (stage 3) have not been implemented to support information and knowledge-sharing activities. Digitalization (stages 1 and 2) capabilities have been implemented to various extents among the structural areas. However, shop-floor operators are working in a pre-digitalization stage.

For the studied companies, the future development concerning the sharing of information and knowledge in a human-focused Industry 4.0 context needs to start with digitalization for operators. To achieve visibility (stage 3) for integration of IT systems, operators need to catch up with office workers in terms of available IT systems that can support their information and knowledge needs. In further advancing towards Operator 4.0, the characteristics of Assembly Systems 4.0 hint at a possible near-future outlook in stages 3, 4, and 5.

4.4 PAPER III

Title: **Forming a Cognitive Automation Strategy for Operator 4.0 in Complex Assembly**

Short Description

Given today's technological advances in the area of Industry 4.0, having a strategy for cognitive automation solutions is crucial. Operator 4.0, will have to handle and manage a range of different work tasks, from learning new tasks to solving difficult problems and initiating changes. Thus, a specific strategy for the design of cognitive automation solutions is needed, to support operators as they move between these tasks. The suggested strategy has three steps: (1) selecting assembly modes, (2) choosing the level of cognitive automation carrier, and (3) suggesting cognitive automation content. It is important that the operator is part of the design and that the solution supports movement between the *learning*, *operational*, and *disruptive* modes. Such a strategy could support manufacturing companies in meeting challenges regarding social sustainability. For example, stress, attractive workplaces, and demography changes, as well as system transparency and complexity.

Main Results

The learning, operational, and disruptive phases use different cognitive processes and are based on a theory of operator work concerning learning, cognition, and disruptive work, as listed in Table 4.5. Whenever an operator needs to learn something new, he or she is working in the learning phase. To support this type of behaviour, the operator needs to be actively aware and reasoning. These non-automatic processes are often energy and time-consuming (Evans, 2003; Tsujii and Watanabe, 2009). In the operational phase, the operator then needs to work based on own experiences and skills. For the disruptive phase, the operator needs to give conscious thought to a solution. This means using reasoning and intuition. In other words, both knowledge-based and rule-based behaviours are used.

Table 4.5. Model for learning, operational and disruptive phases in Paper III.

Phase of assembly work	Desired operator behaviour	Support needed by operator
Learning	Knowledge-based	Reasoning
Operational	Skill and rule-based	Intuition
Disruptive	Rule and knowledge-based	Reasoning and intuition

Discussion and Conclusion

In supporting Operator 4.0, this paper argues that work type (that is, work content) is connected to knowledge levels and cognitive processes. Thus, a strategy was formed to support this. Since Operator 4.0 will carry out many different tasks, it is crucial to design cognitive automation that supports different types of tasks. The strategy has not been fully used in industrial applications but it has been tested. The learning-operational-disruptive modes match models for knowledge levels, cognitive processes, and previous research within the area. This provides industry with a valuable first step in supporting work tasks within the suggested modes. The modes could therefore be used to analyse, quantify, and support parts of Operator 4.0 work tasks and may be considered an important first step in forming a strategy.

4.5 PAPER IV

Title: **Industry 4.0 Maturity and its Implications for Information Sharing on Shop Floors**

Short Description

In this paper, the Industrie 4.0 Maturity Index is applied to identify and understand the maturing towards Industry 4.0 of eight shop-floor cases at five Swedish companies. In general, the maturity model was applied to the cases using a series of research methods. First, generic questions were formulated for all cases. Then a preparatory workshop was run for each case, followed by an adaptation of the generic questions. This was in preparation for the specific factory tours and semi-structured interviews with employees. An analysis was made based on data thus collected. The results were finalized as a consolidated assessment alongside follow-up questions and presented to company employees.

The five manufacturing companies were selected with the aim of comparing shop floors with different production characteristics, such as production volume, product variety, and takt times. Different cases at the same companies were also selected, so that similarities and differences could be highlighted. The five companies, the eight cases, and some production characteristics are listed in Table 4.6. Note that these companies and cases are not the same as those in Paper II.

Table 4.6. Cases in Paper IV.

Company	Cases	Product volume	Product variety	Assembly time
A	A1, A2, and A3	Low	Very high	Approx. 1 workday
B	B	High	High	Around 7 minutes
C	C1	High	High	Around 1 minute
	C2	Low	High	Approx. 1 workday
D	D	Very low	Low	Approx. 1 month
E	E	Low	High	Around 1 workday

Main Results

The results are presented in two parts. First, the Industrie 4.0 Maturity Index model is analysed. This produced a matrix that served as an assessment basis for the cases' information-sharing activities. Second, the outcome of the maturity assessment for each case is presented.

The model's four areas and its subdivisions entail eight different principles. These principles (across the six maturity stages) yield a matrix of 48 possibilities. While Schuh et al. (2017; 2020a) provide rich descriptions of these, an analysis from a human-centred, shop-floor perspective guides the model and supports an understanding of how sharing data, information, and knowledge is affected on shop floors. Table 4.7. presents this, plus the 48 possibilities and their capabilities. This matrix also serves as a guide to how the maturity level within the different cases was assessed.

Table 4.7. Matrix of the principles and stages of digital maturity.

Areas	Principle	1. Computerization	2. Connectivity	3. Visibility	4. Transparency	5. Predictability	6. Adaptability
Resources	Structured communication	Machines not connected. Operators have no digital communication tools.	Machines connected to a local computer. Operators have no digital communication tools.	Automatic, continuous data collection from machines. Operators can have mobile communication devices.	Automatic, event-driven data collection from machines (using open standards). Operators use a collaborative platform for communication.	Machines can be monitored and controlled with mobile devices. Collaborative platform can give timely notification of actions to relevant people.	Machines interact as agents within a network.
	Digital capability	Manual identification of material, tools, and products. Operators set machine parameters manually.	Automatic identification of material, tools, and products on the type level. Operators set machine parameters using recipes. Operators use intended IT systems.	Automatic identification of material, tools, and products on order level. Machine parameters set automatically. Machines can collect process data.	Operators can use IT systems beyond standard functionalities (required for their role). Machines can easily be reconfigured to carry out new tasks.	Operators get decision support from machines.	Machines adapt autonomously and collaborate with operators.

Table 4.7 (cont.). Matrix of the principles and stages of digital maturity.

Areas	Principle	1. Computerization	2. Connectivity	3. Visibility	4. Transparency	5. Predictability	6. Adaptability
Information systems	Information processing	Operators get information on paper. No IT infrastructure strategy.	Operators can search for information on different IT systems.	Operators presented with important information. Real-time data can be collected and some data is analysed and visualized.	Operators presented with important information and content changes to the situation. Real-time data collected and analysed. Strategy for handling system failures.	Operators presented with suggested actions based on real-time analysis. Future IT infrastructure needs suggested by the system.	Autonomous decisions presented to operators. IT infrastructure adapts to future needs.
	Integration of IT systems	Machines not connected. No integration of IT systems.	Data can be trusted, used, and further processed manually. IT systems can send data along the process.	Real-time data with read access. Data redundancy is avoided. IT systems can send data bidirectionally. Data quality problems documented and fixed.	Real-time data with read-and-write access. Automated data cleansing to ensure further data processing.	Automated quality evaluation of datasets.	Automated quality assurance of datasets. IT functions offered through well-defined services.

Table 4.7 (cont.). Matrix of the principles and stages of digital maturity.

Areas	Principle	1. Computerization	2. Connectivity	3. Visibility	4. Transparency	5. Predictability	6. Adaptability
Organizational structure	Organic internal organization	Collaboration occurs only within functional units. Managers make all decisions.	Collaboration occurs between functional units. Operators make operative decisions. Operators' ideas collected and evaluated. Some project management processes exist.	Collaborative platform used by operators. Some agile project management principles applied. Multi-dimensional targets communicated (e.g. SQDC).	Operators form long-term expert communities. Operators involved in the innovation process. Targets for non-process specific activities exist.	Non-financial individual incentive systems used (e.g. education, freedom, responsibilities). Systematic follow-up of innovation process (e.g. PDCA).	Operators active in several expert communities. Operators can explore and pursue own ideas. Target systems consider spontaneous engagements.
	Dynamic collaboration in value networks	Core competencies unknown. Suppliers managed inflexibly. No capacity management.	Capacities managed through internal mechanisms.	Core competencies known. Supplier relationships actively managed. Partners can support capacity variations.	Core competencies actively managed in the value network. Capacities can be sold or purchased.	Need for new core competencies can be predicted. Capacity fluctuations can be predicted and managed.	New core competencies developed. Automatic and order-specific selection of suppliers from value network. Capacities can be sold and purchased on open market.

Table 4.7 (cont.). Matrix of the principles and stages of digital maturity.

Areas	Principle	1. Computerization	2. Connectivity	3. Visibility	4. Transparency	5. Predictability	6. Adaptability
Information systems	Social collaboration	Hierarchical organization. No dedicated IT systems.	Hierarchical organization. Some dedicated IT systems exist but workarounds may occur.	A hierarchical organization with clear communication structure (e.g. daily planning meetings). Workarounds not allowed by IT systems.	Democratic and cooperative organization with demand-based communication. Operators understand why IT workarounds should be avoided.	Operators collaborate outside hierarchical structures, supported by flexible IT systems.	Operators collaborate in autonomous teams.
	Willingness to change	Operators rely on own experience (even if data exists).	Data considered for some decisions. Operators share knowledge informally. Changes controlled by management but explained and accepted over time.	Decisions often backed by data. Operators’ knowledge collected and competence matrix exists. Continuous improvements initiated mostly by operators. Mistakes documented and can lead to new standards.	Decisions based on data analysis. Operators’ knowledge processed and shared. Operators involved in developing training. Operators actively contribute to continuous improvements. Mistakes analysed.	Decisions supported by predicted scenarios. Changes communicated early operators are involved. Error-proofing actions controlled and followed up.	Decisions largely automated. Operators’ lifelong learning includes new skills and responsibilities. Operators share responsibility for changing processes and their requirements. Continuous change anticipated.

The data collection results in an understanding of what types of data, information, and knowledge are shared in each case. Analysing this sharing enables the maturity stages in the cases to be identified for the principles. Each principle may include several capabilities. This leads to the results in Table 4.8, which presents average scores. This is because the cases exhibit evidence of capabilities at different stages for each of the principles.

Table 4.8. Results of maturity assessments (as maturity scores) of the eight principles for each of the cases in Paper IV.

	Resources		Information systems		Organizational structure		Culture	
	Structured communication	Digital capability	Information processing	Integration of IT systems	Organic internal organization	Dynamic collaboration in value networks	Social collaboration	Willingness to change
Case A1	1.0	1.1	2.3	1.4	2.5	2.8	3.3	2.7
Case A2	1.0	1.1	2.3	1.4	2.5	2.8	3.3	2.7
Case A3	1.0	1.1	2.3	1.4	2.7	2.5	3.3	2.7
Case B	2.3	2.2	2.7	2.3	2.8	2.3	3.0	2.3
Case C1	2.3	2.6	2.3	2.7	2.1	2.3	2.7	1.8
Case C2	2.0	1.8	2.8	2.6	2.0	2.3	3.7	2.2
Case D	1.7	1.8	3.3	2.6	2.5	2.5	3.3	2.5
Case E	1.8	2.3	2.8	2.2	1.9	3.3	3.5	2.8

Resources. None of the cases is assessed as having reached visibility (stage 3) in the resources area. Cases A1, A2, and A3 are at 1.0 and 1.1 for structured communication and digital capability, respectively. Cases C2 and D have reached a higher maturity, with the use of more digitally connected tools. For cases A1, A2, and A3 this is still manual. Cases B and C1 (with shorter takt times than the others) have developed resources, in terms of power tools, that can automatically store and transfer data. In the other cases, this is done manually.

Information systems. Compared to resources, there are greater differences in the results between the two principles. For Cases A1, A2, and A3, the IT systems they use can store data or information, which allows for manual processing (information processing 2.3). However, these IT systems are not interconnected and thus require manual transfer of the data and information (integration of IT systems 1.4). Similarly, for Cases B and C2, information processing (2.7 and 2.8) is further developed than integration of IT systems (2.3 and 2.6). Their information systems are connected, but still require operators to actively find relevant information. Unlike the other cases, Case C1 with the shortest takt time, has instead reached a higher level of integration of IT systems (2.7) than information processing (2.3). This can be explained by the greater amount of data automatically shared between the different IT systems. Due to the short takt time, operators are not required to conduct manual data exchanges. Case D differs from the other cases, with an information processing level of 3.3. This is because, for product development, the assembly instructions require processing of various information sources from production and 3D models. However, this integration of information from different IT systems is not automatic and thus scores 2.6.

Organizational Structure. All cases are at stage 2 (connectivity) and progressing towards stage 3 (visibility). There are similarities between the studied companies regarding organizational structure, which may be due to their common national origin (Swedish). There is generally a less hierarchical organization which allows need-based collaboration within other groups in the respective companies (organic internal organization) and internal management of capacities (dynamic collaboration in value networks). Cases C1 and C2 score lower and Cases A1, A2, A3, and D score higher. This could be explained by the fact that the rules of communication are less strict, allowing operators not restricted by short takt times to contact other groups that can support their work.

Culture. Here, there is more of a spread among the cases. Concerning social collaboration, all cases have clear communication structures that support collaboration. However, Case C1 has the shortest takt time, which restricts opportunities for flexible collaborations. Case B has the second shortest takt time but allows for collaboration with other operators. Cases A1, A2, A3, and D have much longer takt times; operators have time and are encouraged to collaborate with other functions in solving assembly-related problems. Case C2 is a quality inspection station. Whilst it has productivity goals, it does not abide by traditional takt time requirements. Instead, the operators collaborate with geometry assurance engineers in their daily work. When it comes to change and improvement efforts, all the cases base their decisions mainly on experiences supported by some data, which is stage 2 (connectivity). However, the way operators share knowledge with each other varies. For example, in Case C1, sharing is less common than in Cases C2 and B and, when it does take place, is done informally between operators (1.8, 2.2, and 2.3). For Cases D, A1, A2, and A3, information and knowledge-sharing among operators is better encouraged and supported, which increases their maturity level (2.5 and 2.7).

Discussion and Conclusion

In general, manufacturing companies have attained connectivity maturity and, with their current implementations of Industry 4.0-related technologies, are heading towards visibility. However, more efforts are needed if they are to become established in the visibility stage, both regarding technical aspects and organizational and cultural aspects.

A higher level of maturity towards Industry 4.0 enables new approaches to information sharing on shop floors. With the opportunity to share information more effectively, operators can benefit from better information. For example, assembly instructions that fit operators' cognitive needs.

Using a maturity model helps estimate companies' current situation but cannot be seen as a simple solution to implementing Industry 4.0. Nevertheless, it is useful as a basis for discussion and in creating roadmaps and concrete project proposals that can move companies stepwise towards attaining higher levels of maturity. This is also evidenced by the differing characteristics of different companies' operators. The varying necessity of sharing different types of information can be supported by the same maturity model.

This paper provides results in terms of the maturity levels of five companies. However, more research is needed to understand how implementing Industry 4.0 concepts with transparency and predictability capabilities will affect the way information is shared on shop floors and how it will affect the work of operators.

4.6 PAPER V

Title: **Exploration of Digitalized Presentation of Information for Operator 4.0**

Short Description

This paper explores five cases of digitalized information presentation. The production characteristics and operators' cognitive situations vary across the cases. Based on these variations, the cases have independently developed ways of presenting information more effectively. These are described in terms of carrier and content and are intended to support operators. These case solutions are then assessed based on their contribution to ensuring high-quality information.

The five cases at the four companies are listed in Table 4. Note that the companies in this paper correspond to the companies in Paper IV, except for one company in Case E. However, these cases do not refer to the same cases as Paper IV. Paper IV scopes a productions system, while this paper focuses on information presented to operators.

Table 4.9. Cases in Paper V.

	Production characteristics			Operator's cognitive situation	
Case	Product volume	Product variety	Assembly time	Assembly mode	References
A	Low	Very high	Approx. 1 workday	Learning	Helldén and Karlsson (2020) Holmgård (2020)
B	High	High	Around 7 minutes	Operational	Delin and Jansson (2015) Eriksson and Johansson (2017) Asklund and Eriksson (2018) Bäckström and Westberg (2020)
C1	Very high	High	Around 1 minute	Operational	Palmqvist and Vikingsson (2019) Andersson and Trogen (2020) Palmqvist et al. (2020)
C2	Low	High	Approx. 1 workday	Operational	Billskog Johansson and Chowda Shetty (2020)
D	Very low	Low	Approx. 1 month	Learning	Hellgren and Munge (2018)

Main Results

As evidenced by the circumstances in Table 4.9, the different cases have developed different solutions to supporting their operators cognitively. These are listed in Table 4.10. These varying types of information carriers have different information content depending on the type of information operators need. Further, for information to be properly presented, information carriers and content need to put various demands on the technical interoperability and integration of IT systems.

Table 4.10. Carrier and content of the digitalized information presentation in Paper V.

	Information support technology		Future outlook on digitalization opportunities for presenting information
Case	Carrier	Content	
A	Desktop computer with two monitors	2D drawings and text instructions	Trial runs with work orders
B	Touchscreen monitor	Step-by-step text and pictures	Development of interoperability to facilitate automatically generated instructions
C1	An automatically updated monitor	Symbols reminding of important considerations	Scaling up to more workstations
C2	Smartphone placed on forearm	Specification of measurement information	Application in other workstations
D	Desktop computer	Interactive 3D models	Augmented reality application of 3D models

Case A is a manufacturer of custom-engineered antennas and circuit boards. These are assembled in cleanrooms and operators log onto the ERP system for each work order, where documents are attached. There are two main types of documents that operators use as instructions:

- *assembly procedures*, detailing step-by-step assembly operations (what to assemble). This document also contains hyperlinks referencing other documents, such as quality standards, process descriptions, and project-specific documents.
- *quality standards*, clarifying details on quality demands for operations (how to assemble). Experienced operators familiar with the operational standards use this document as a reference, while novice operators consult it more frequently.

Based on information that can be found in the ERP system (assembly procedure documents and quality standards documents), Case A developed a model for disseminating information and a concept for presenting it (Holmgård, 2020; Helldén and Karlsson, 2020). A model of where information exists and how it disseminates throughout Case A was created to ensure the information could be accessed digitally and then relevant details presented to operators. A concept of how to present this information visually was developed concurrently, to simplify operator access to relevant information. While information from the ERP system may be retrieved with little change for planners, the concept requires technicians and designers to disseminate it differently. Figure 4.1 is a screenshot of an operator's view, combining work order-specific information from the ERP system, assembly procedure documents and quality standards documents. A trial run is planned for Case A, to validate the information presentation concept. This will have working demonstrators and work orders.

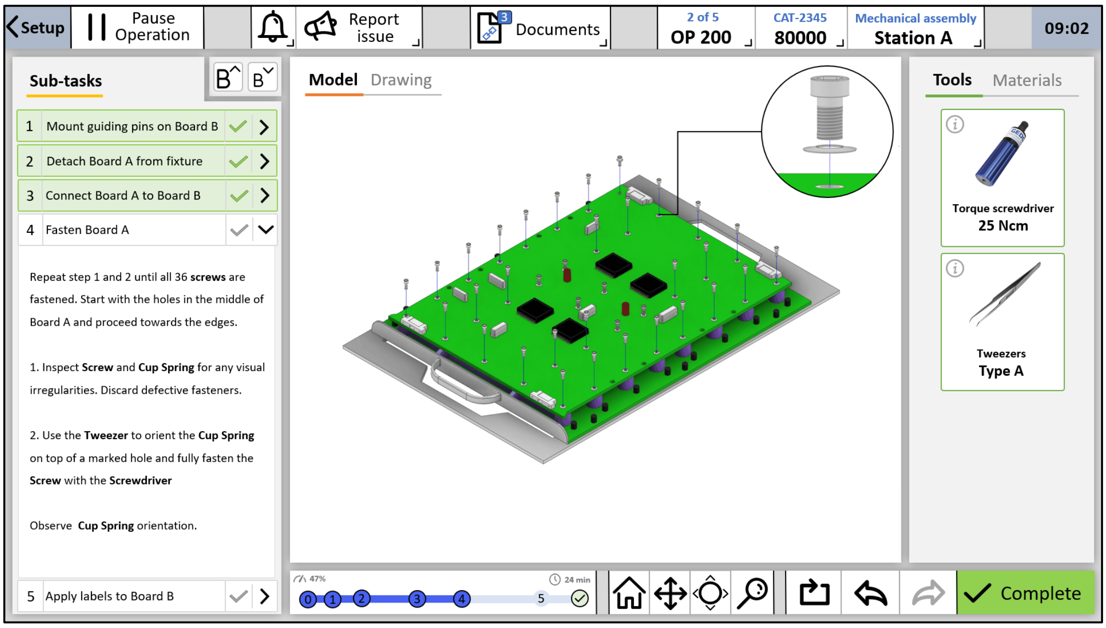


Figure 4.1. Concept for digitalized presentation of information in Case A (Helldén and Karlsson, 2020).

Case B involves pre-assembly in a final assembly plant, where operators assemble mid-sized rigid and flexible components before the product moves on to the main assembly line. There are two main document types supporting operators in their assembly work:

- *assembly instructions*, a text-based bill of materials is printed out on paper. This consists of a list of all the components and materials used in the assembly procedures (what to assemble).
- *standard operating procedure* documents. These contain information which the assembly instructions lack, including images and detailed instructions on the assembly procedure (how to assemble). These documents are mostly used for training purposes.

In Case B, a concept was developed whereby various amounts of information are presented depending on the operator's experience (Asklund and Eriksson, 2018). This concept features mainly picture-based, step-by-step instructions, accompanied by text. For experienced operators, the information presented comes mainly from the assembly instructions. Meanwhile, for novice operators, information from the standard operating procedure is also presented. An example of the interface is shown in Figure 4.2. So that this concept can function on a large scale, Case B developed an information model intended to generate instructions automatically (Bäckström and Westberg, 2021).

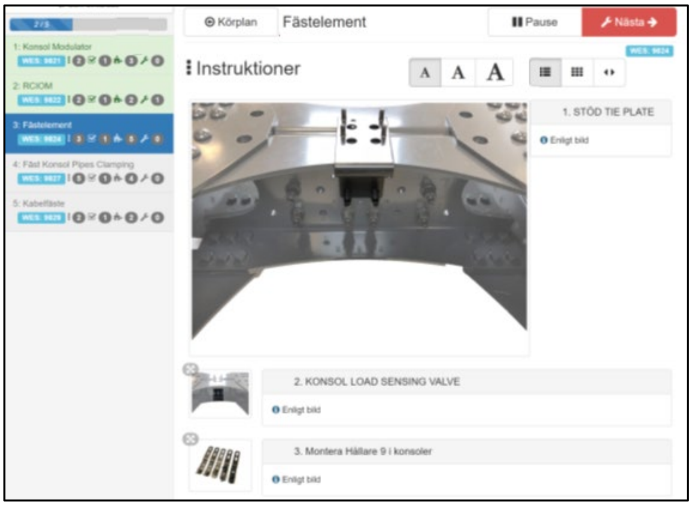


Figure 4.2. Concept for presenting digitalized information in Case B; example for experienced operators (Asklund and Eriksson, 2018).

For Case C1, with its short takt times, operators are expected to learn operations by heart. In other words, *what to assemble* and *how to assemble*. A concept of digital assembly instructions was developed, to decrease quality-related issues and cognitive workload on operators (Palmqvist and Vikingsson, 2019; Palmqvist et al., 2021). This was implemented at two workstations on the assembly line (Andersson and Trogen, 2020). The concept focuses on providing reminders that highlight important tasks (a subset of *what to assemble*), frequent quality issues and infrequent product variations. These reminders are shown as symbols, presented on monitors to the operator as the product moves to their workstation. This is shown in Figure 4.3.

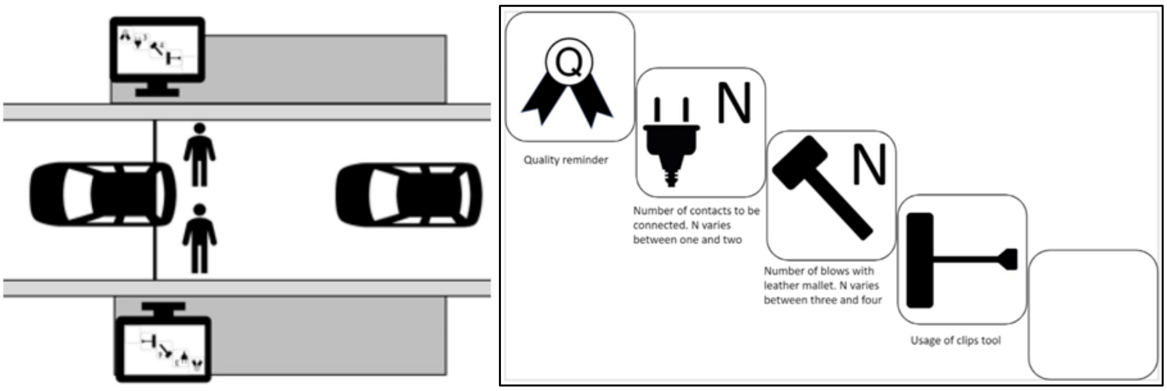


Figure 4.3. Placement of monitors (left) and example of presented information (right) in Case C1 (Andersson and Trogen, 2020).

For Case C2, the off-line quality inspections station, a smartphone solution was implemented to reduce operators' distance to information. In other words, improving accessibility (Billskog Johansson and Chowda Shetty, 2020). The development of interoperability features was designed to show proof-of-concept within the framework of existing infrastructure. A locally hosted server was programmed with HTML, allowing smartphones to be connected. The synchronization of instructions and measurement data was enabled using Python scripts. Mounting the smartphone on the operator's forearm means fewer interruptions to the workflow, as shown in Figure 4.4.

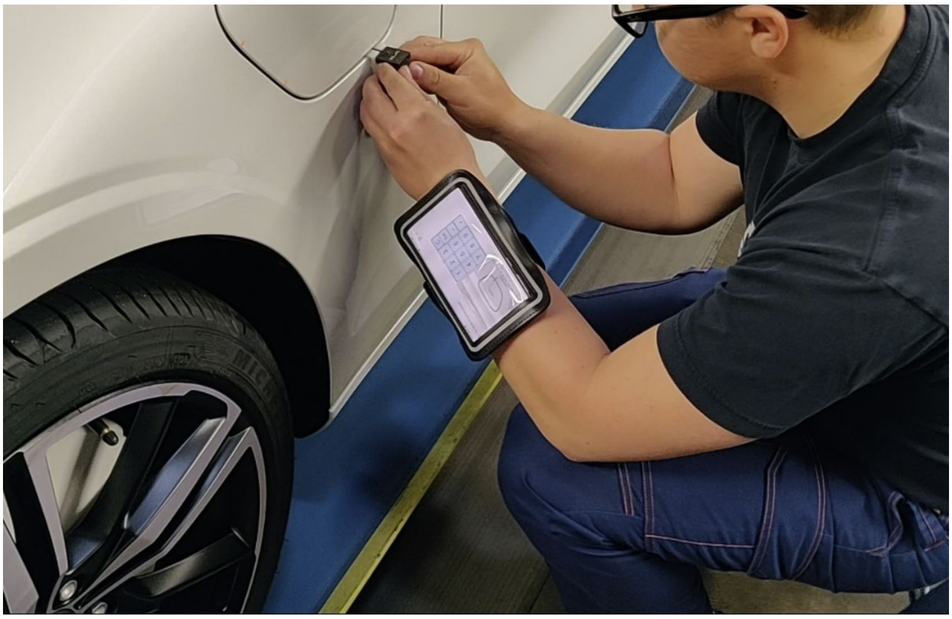


Figure 4.4. Operator taking measurements, using information presented on a forearm-mounted smartphone, in Case C2 (Billskog Johansson and Chowda Shetty, 2020).

For Case D, due to the infrequency of repeated assembly operations, operators are not expected to learn operations by heart. To meet the high-quality demands and address operational infrequency, operators are provided with step-by-step assembly instructions based mainly on 3D models and accompanied by descriptive text instructions. The models are based on underlying design models, further adapted and exported to a lightweight format presented to the operator. This model-based design format of the instructions is shown during assembly on desktop computers a couple of meters away from the product itself. An operator can interact with, zoom in and out, and rotate these 3D models. An example of this interface is shown in Figure 4.5. Typically, an operator needs to remember a series of operations. This is because it is difficult for an operator to get to the instructions at the computer station when they are working inside or on the other side of the product.

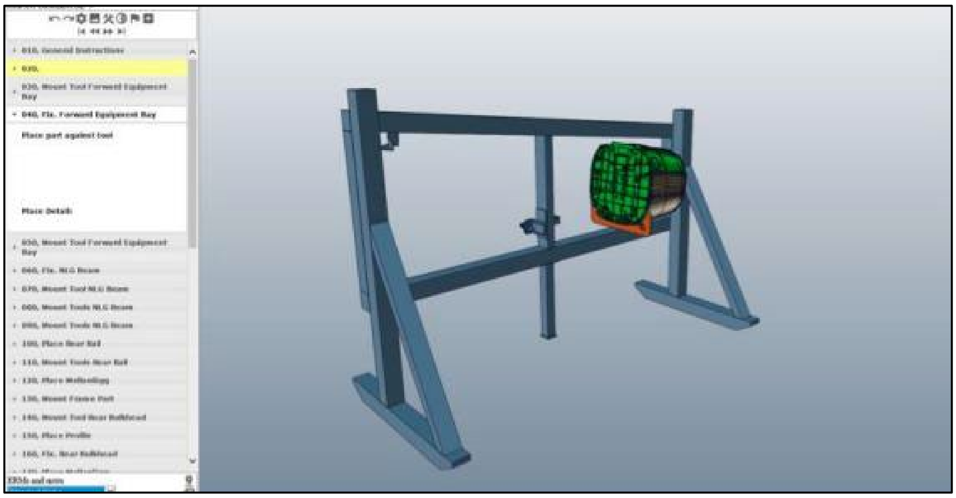


Figure 4.5. Assembly instructions interface with 3D model, in case D.

A demonstrator with augmented reality goggles was developed, to shorten the distance between the operator and their instructions. This demonstrator uses the same underlying design models as in the standardized assembly instructions interface. The augmented reality goggles are programmed to recognize the shape of a previously assembled product and overlay an image of the next component to be assembled in the 3D space. As a next step, the plan is to use this approach to presenting information via the augmented reality demonstrator in Case D's company training facilities, where new operators are trained. After pilot testing in the training facilities, Case D will then gradually implement this assembly concept using larger distances between operators and the standardized assembly instructions.

Discussion and Conclusion

Table 4.11 summarizes the five cases. Its focus is on evaluating the demands placed on the abilities of individual operators and the technical capabilities needed to support them and their assembly modes.

The low product volumes and infrequency of assembly operations puts the operators of Cases A and D in a learning phase. Such burdens on operators to repeatedly learn and understand operations heightens the need for a level of automated cognitive support to decrease demand on operators' abilities. The high levels of complexity in Cases B and C1 are evidenced by the high product volumes and product varieties. Case B prioritized the adaptability of assembly instructions to match individual operators' varying needs and wishes for such a support tool. However, Case C1, with its much shorter takt time and expectation that operators would learn operations by heart, prioritized adaptation of the presented information according to product and quality necessities. By comparison, Case C2 also has operators in an operational mode in their assembly work but, due to lower product volume and longer time, the complexity is slightly lower.

With increasing levels of physical, sensorial, and cognitive automation, operators are provided with more support in their daily work. There are fewer demands on individual abilities and more focus on helping their existing abilities to flourish. However, with increased automated support, companies introduce a reliance on automated support tools to perform and function. This creates a demand for the technical capabilities of physical, sensorial, and cognitive automation.

Table 4.11. Rationale for presenting information and its effects on information quality in Paper V.

		Production characteristics				Cognitive automation strategy	Demands on individual abilities		
Case		Product volume	Product variety	Assembly time per workstation	Operator choice complexity	Assembly mode	Physical abilities	Sensorial abilities	Cognitive abilities
A	To lower cognitive workload for operators	Low	Very high	Takes approximately 1 workday	Very high	Learning	High demands Low level of automated support	High demands Low level of automated support	Medium demands Medium level of automated support
B	To lower cognitive workload for operators	High	High	Takt time around 7 minutes	High	Operational	Medium demands Medium level of automated support	High demands Low level of automated support	Low demands High level of automated support
C1	To improve assembly quality	Very high	High	Takt time around 1 minute	High	Operational	Medium demands Medium level of automated support	Medium demands Medium level of automated support	Medium demands Medium level of automated support
C2	To present information closer to the assembly area	Low	High	Takes approximately 1 workday	Medium	Operational	High demands Low level of automated support	High demands Low level of automated support	Medium demands Medium level of automated support
D	To present information closer to the assembly area	Very low	Low	Takes approximately 1 month	Low	Learning	High demands Low level of automated support	High demands Low level of automated support	Low demands High level of automated support

5

DISCUSSION

This chapter elaborates on and answers the research questions. Furthermore, implications for academic research and the manufacturing industry are laid out. Finally, the quality of the research and its limitations and reflected upon.

5.1 EFFECTIVE INFORMATION SHARING IN PRODUCTION SYSTEMS AND ON SHOP FLOORS

Both research questions relate to *effective information sharing*; RQ1 in *production systems* and RQ2 on *shop floors*.

A subset of all the information shared in a production system gets presented to shop-floor operators as cognitive support. As shown in Papers II and IV, such information includes, but is not limited to, work orders, lists of operations and assembly instructions. Further, information presented to shop-floor operators relates to learning new tasks or conducting tasks in operative mode, as seen in Papers III and V.

Thus, the concept of effectiveness is judged differently for information dissemination in production systems and information presentation on shop floors. However, both take a qualitative approach.

In production systems, effective information sharing relates to expediency and the collection, analysis and dissemination of information to those for whose work the content is relevant. Dissemination therefore depends on interoperability between IT systems. With digital technologies, information can be disseminated more effectively in production systems in terms of expediency, as explored in Paper IV.

On shop floors, effective information sharing relates to the quality and visual presentation of information to the operator. Such presentation therefore depends on how operators will use it. Digital technologies may be used to present and visualize different types of information, such as assembly instructions, as shown in Paper V.

As found in Paper I, using digitalization requires two approaches. First, a strategic approach whereby companies can effectively disseminate information throughout their production system (meaning horizontal, end-to-end engineering, and vertical integration using new solutions for disseminating information, as explored primarily by RQ1 and Papers II and IV). Second, identifying and supporting individual operator's need for relevant information, with shorter feedback loops at the right place and in the right time, as explained primarily by RQ2 and Papers III and V.

Connecting to the aim of this thesis, the two RQs contribute to two approaches to digital transformation. First, by applying the methodological strategy outlined in Paper IV, companies can be supported in their initial digitalization for disseminating information. Second, by comparing the digital assembly instructions analysed in Paper V, companies can be supported in presenting instructions. Together, these two approaches contribute to different strategies for effective information sharing. It is important to consider these in the context of digital transformations towards Industry 4.0 and Operator 4.0.

5.2 DIGITAL MATURITY AND THE EFFECTIVE DISSEMINATION OF INFORMATION IN PRODUCTION SYSTEMS

RQ1 asked: *How can assessing digital maturity facilitate the effective dissemination of information in production systems?*

Assessing Digital Maturity

The main outcome of supporting the assessment of digital maturity was presented in Table 4.7. The different areas and their principles provide a holistic approach to maturity assessments and digital transformations towards Industry 4.0 in a production systems context.

Resources: digital capability (both operators' use of digital technologies and the capabilities of those technologies) play an important role. Connecting machines and tools shorten the time spent disseminating information. Increased digital maturity in terms of resources enables information to be collected and may also improve the traceability of tools, materials, and products.

Information systems: interoperability enables the integration of information sources and recipients; this facilitates the dissemination of information between IT systems and processing of that information. With IT systems integrated in this way, having trust in the quality of disseminated information becomes important. Increased digital maturity in information systems facilitates an integrative information flow, as shown in Figure 1.2.

Organizational structure: digital transformations also require organizational maturity. This supports the new digital technologies which allow the digital maturity of the resources and information systems to increase. An organization's processes need to support how employees want to work but also support the new ways of working enabled by having more mature resources and information systems. It therefore becomes important to consider how information quality is ensured and how information flows.

Culture: digital transformation infers change, concerning both the digital technologies and organizational processes that affect how employees work. Therefore, willingness to change and an appropriate degree of trust in digital technologies are important. For a higher level of digital maturity, employees will need to understand how decisions are made; in other words, the information upon which decisions are based. This affects whether the resources and information systems will be used.

Comparing Digital Maturity

The current production-related information-sharing practices of the companies studied in Papers II and IV is at a pre-Industry 4.0 maturity stage. While the two small companies in Paper II are at the initial computerization stage, the five larger companies in Paper IV have achieved connectivity maturity and are making strides towards visibility. This is comparable to the position of similar companies in Western industries (Schuh et al., 2020b).

A higher Industry 4.0 maturity level enables new approaches to how information can be shared on shop floors. With the opportunity to share information more effectively, operators can benefit from better information, such as assembly instructions that fit operators' cognitive needs.

Advancing maturity levels enable new capabilities. Once visibility has been achieved, moving on to the transparency level, companies gain the capability to bring users more automatic situation-adapted information in near real-time, instead of users having to actively seek information. Most of the companies in Papers II and IV are aiming for this level of maturity.

Paper II analysed how using some Industry 4.0 concepts requires visibility, while others use transparency and predictability. As shown in Table 4.4, concrete examples were given of different tools that could be implemented. Paper IV illustrates this at higher resolution, detailing each principle rather than each area as in Paper II.

Digital Transformation of Production Systems

Using a maturity model helps estimate companies' current situation. However, it cannot be seen as a simple solution to implementing Industry 4.0. Nevertheless, it is useful as a discussion basis for creating roadmaps and concrete project proposals to steadily move companies towards higher maturity. This is also evidenced by the different characteristics of different companies' operators. The varying necessity of sharing different types of information may be supported by the same maturity model.

For companies to make a digital transformation (that is, to embrace parts of Industry 4.0 and its related technologies), they need to assess their current situation. In Papers II and IV, this was done using a maturity model. Based on this mapping of current Industry 4.0 capabilities, developmental decisions could be made for the cases in Paper IV.

In Paper II, the current state was compared to Assembly Systems 4.0 concepts. This can help in setting digital transformation goals, as listed in Table 4.4. These Assembly Systems 4.0 tools provide new capabilities for companies to share information. Paper IV compared the current state of the cases, to provide goals that were attainable in the near future.

The comparisons made in Paper II and IV provided a toolbox of possible development goals for companies, enabling them to see what could be achieved through digital transformation. This was done conceptually in Paper II, with Assembly Systems 4.0 tools up to stage 5, predictability and empirically in Paper IV, with cases up to stage 3, visibility.

New capabilities can be obtained at later maturity stages. However, no company has yet gone beyond stage 4. Accordingly, Paper II stakes out possible capabilities further into the future, while Paper IV provides insight into what is possible in the near future, based on the state-of-the-art of its cases.

While the cases in Papers II and IV give concrete examples of specific capabilities, Table 4.7 from Paper IV contains generic capabilities that can be applied differently depending on companies' specific challenges.

Answering RQ1: How can assessing digital maturity facilitate the effective dissemination of information in production systems?

From a production systems perspective, the approach used in Paper II and later refined in Paper IV, shows that the selected maturity model was used to assess current information disseminating capabilities.

Assessing digital maturity can facilitate effective information dissemination in production systems by serving as a starting point for formulating development plans to increase digital maturity. An increase in digital maturity to a higher stage provides companies with new capabilities for disseminating information.

The seven manufacturing companies in Papers II and IV have varying levels of digital maturity, ranging from still being dependent on paper instructions during final assembly to sharing information using IT systems visible from different parts of the production system, and simplifying the information-sharing process for source and recipient actors. Between paper-based sharing and visibility lies initial computerization and connectivity. However, these levels still require manual effort to make information sharing work. Moreover, maturity assessments (as conducted in Paper IV) may be used to facilitate identification and creation of development plans to make disseminating information more effective and, by extension, contribute to a digital transformation to Industry 4.0.

5.3 DIGITAL TECHNOLOGIES AND THE EFFECTIVE PRESENTATION OF INFORMATION TO OPERATORS ON SHOP FLOORS

RQ2 asked: *How can applying digital technologies facilitate the effective presentation of information to shop-floor operators?*

Cognitive Situation of Operators

The operators' cognitive support needs (explained in Paper III) and the comparison of assembly instructions (in Paper V) show that different operator situations and different final assembly characteristics require different types of assembly instructions to present information effectively to operators.

As shown in Paper III, most assembly work occurs in an operational phase, in which digital assembly instructions should provide intuitive support as operators often already know their tasks by heart. While this may be accurate in high-volume production, for production systems with high degrees of product variety, digital assembly instructions must provide more support for operator reasoning. This is because such assembly work requires operators to learn as they go along.

For short takt time, high-volume production, the assembly instruction system can recognize the product variant and then present the operator with condensed instructions highlighting important information. For long takt times with high degrees of product variety, integrating IT systems can leverage information from product designs and highlight salient details for operators.

Digital Transformation on Shop floors

Implementing digital technologies can provide cognitive support to shop-floor operators. As listed in the company cases of Table 4.9, several digital transformations of assembly instructions and information presentation are underway.

Different approaches to presenting information are explored, according to operators' needs and the production characteristics. In the case of higher degrees of digital maturity (as in Paper IV), information can generally be customized and made more effective for the operator (Paper V).

Concerning transformation to Operator 4.0, Table 2.2 exemplified five cognitive operator interactions. While not directly implementing the specific Operator 4.0 concepts, the cases in Paper V show first steps in this direction, as listed in Table 5.1.

Table 5.1. Operator 4.0 and trajectory for Paper V cases.

Operator 4.0	Short description	Paper V cases trajectory
Augmented operator	Augmented reality technology that overlays information for the operator.	D: augmented reality goggles.
Virtual operator	Virtual reality technology with immersive simulations to support decisions.	-
Smarter operator	Intelligent personal assistants can help operators manage tasks and interact with automation.	A, B: instructions may be adapted dynamically, based on operator preferences.
Social operator	Social networks help operators create communities, which promote information sharing.	C2: forearm-mounted smartphones can also help operators share measurement data and product information with each other.
Analytical operator	Big data analytics help operators make better data-driven decisions.	C1: instructions automatically updated on monitors. In the future, the way these are updated may depend on more factors.

Information Quality of Assembly Instructions

Different digital technologies have varying advantages and disadvantages in their presentation of information. For presenting information to be effective, the information content needs to be useful for the operators, as listed in Table 4.10. The information quality attributes determine which way cognitive support is useful for the operators.

Answering RQ2: How can applying digital technologies facilitate the effective presentation of information to shop-floor operators?

From a shop-floor operator perspective, different cognitive support needs are explained in Paper III. The subsequent comparison of assembly instructions in Paper V shows that on shop floors with different production characteristics, operators face different situations. These require different types of information as cognitive support.

Applying digital technologies can enable new possibilities for presenting information to operators. By demonstrating a variety of approaches to how assembly instructions are designed (in terms of information content), companies can select an approach that comes closer to effective fulfilment of operators' cognitive support needs.

For some assembly tasks (especially if there is a high level of variety that increases the perceived complexity), operators stay in a learning mode of assembly work. In cases of high product variety and short takt times, operators are in an operational assembly mode. The cases in Paper V present condensed information on screens positioned close to operators. For low product volumes and long assembly times, operators stay in a learning assembly mode. The cases in Paper V present extensive information, including computer models and designs. These examples from Paper V facilitate identification of cognitive support needs and any digital solutions that may make presenting information to operators more effective and, by extension, aid the digital transformation to Operator 4.0.

5.4 RESEARCH CONTRIBUTION

As envisioned in the epistemological reflections, the research in this thesis has contributed to the general body of knowledge in both academia and industry.

To Academia

Regarding RQ1, the research work conducted in Papers II and IV assessed the digital maturity of seven Swedish manufacturing companies. These insights helped understand the current state and future challenges for digital transformation to Industry 4.0. This thesis has thus contributed to the general body of knowledge about industrial digitalization.

Regarding RQ2, the research conducted in Paper III conceptualized operators' cognitive needs, while Paper V have evaluated a variety of digital technologies at Swedish manufacturing companies. These insights helped understand how to provide cognitive support for Operator 4.0. This thesis has thus contributed to the general body of knowledge about cognitive automation.

To Industry

The outcomes of RQ1 show different aspects of digital maturity and its role in effective information dissemination in production systems. For the manufacturing industry in general, Papers II and IV provide opportunities for benchmarking. For the six manufacturing companies that participated in Papers II and IV, the assessments of digital maturity were useful in providing insights into the companies' production systems and supporting them in their future endeavours to achieve Industry 4.0. This thesis has thus contributed to the digital transformation to Industry 4.0.

The outcomes of RQ2 show the varying circumstances in which operators work, their varying cognitive support needs and a variety of possible digital technologies that can be applied. For the manufacturing industry in general, Papers III and V provide inspiration for possible solutions to support operators cognitively. For the five manufacturing companies that participated in Paper V, the multiple developments of digital technologies were useful in providing cognitive support for Operator 4.0. This thesis has thus contributed to the digital transformation to Operator 4.0.

5.5 RESEARCH QUALITY

The discussion, including the answers to the research questions, is based on the research conducted in the appended papers.

Concerning the validity of the research, the methodological intention was for these papers to stand on their own by having their own methodologies to allow them to investigate according to their intended aims but also to have varied methodological approaches supporting the elicitation of different types of conclusions. They thus jointly provide both explorations and explanations.

Concerning the reliability of the research, some minor inconsistencies in the data collection were anticipated, because interviewees are human beings who may not always behave as predicted. However, regarding the outlined instrumentalism philosophy, the purpose of the research was to provide useful tools rather than absolute truth. This is judged accordingly in the appended papers.

Reflections on Research Limitations

The variety of ways in how data was collected have affected the quality of the answers to the research questions. In general, the applied data collection methods contributed differently, both when comparing within a case and between cases. As an example for within a case; some information about operators' use of digital tools and interaction with instructions were predominately gathered from interviews and further supported by workshops, gemba walks, or internal documentation to various extents, while for other cases another method was dominant. Similarly, for comparison between cases, most of the gathered information may have come from interviews in one case and workshops or gemba walks in another case. The gathered information was then analysed with the application of the same models. For RQ1, these were the Assembly Systems 4.0 concepts and Industrie 4.0 Maturity Index and, for RQ2, the quality of information attributes and Operator 4.0 typology. By extension, the selected models for categorising the various data sources have shown the versatility of the applied models. This purposeful choice of methods triangulation has strengthened the credibility because of the prolonged engagement in the cases with several methods to reach sufficient saturation. This means that similar phenomena have been studied with different data collection methods. However, this methods variation risks the consistency between cases. Reconnecting to the instrumentalism philosophy and pragmatic approach, the above-mentioned models have been useful for describing the phenomena that were intended from the onset.

While shop-floor operators were the focus of most interviews, workshops, and gemba walks, other stakeholders also participated as data-collection subjects, including team leaders, production engineers, IT technicians, production technicians, quality assurance personnel, research engineers, managers, and so on. The operator focus was motivated by a wish to understand their informational needs, which may have led to a bottom-up organizational bias. Hence, other stakeholders were also included. However, because the case companies are partners in research projects aiming to improve operators' cognitive situation, the other stakeholders may be influenced by their companies' human-centred perspective in the research projects contributing to this thesis. This, despite the author's best efforts to obtain the many relevant data-collection subjects from the varying case companies. For answering the research questions, this operator focus has affected the conclusion in a more operator-positive manner. Consequentially, this thesis emphasises humans at work rather than technology implementation or organizational development, which constitute important aspects for manufacturing companies to consider. However, given that related research concerns with technological development to a large extent and given the human-centred scope of this thesis from its onset, this operator focus was intentional.

RQ1 prioritized more in-depth analyses, rather than comparing a large number of maturity and readiness models, or surveying many companies with rapid self-assessments. RQ2 focused on understanding the needs of operators in relation to the prerequisites of production systems, rather than comparing the various technologies driving Industry 4.0. Thus, by comparison to related research, the content of this thesis has focused on fewer cases but with richer descriptions. In general, there was a trade-off; a sacrifice of tracking broader trends in the manufacturing industry (which was never the intention) in favour of deducing knowledge on how to describe phenomena that affect digital transformations in production systems.

6

CONCLUSION

The aim of this thesis was to formulate strategic approaches towards digital transformation of production systems that facilitate effective dissemination and presentation of information. Thus, two approaches were presented.

The first approach was to assess the digital maturity of production systems. This thesis shows that maturity assessments provide an understanding of current capabilities which, in turn, enables the formulation of goals for digital transformations. It subsequently facilitates the creation of development plans to make disseminating information more effective.

The second approach was to apply digital technologies. Operators work under varying circumstances, requiring varying types of information as cognitive support. This thesis shows that understanding these situational requirements facilitates the selection and subsequent implementation of suitable digital technologies to make presenting information to operators more effective.

An assessment of digital maturity creates a foundation for applying digital technologies. Together, these two strategic approaches to digital transformation demonstrate how digitalization can facilitate effective information sharing in production systems.

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